ARCADIS Design & Consultancy for natural and built assets

Cameco Fuel Manufacturing Inc.

ENVIRONMENTAL RISK ASSESSMENT FOR THE CAMECO FUEL MANUFACTURING FACILITY

November 2016

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Environmental Risk Assessment for the Cameco Fuel Manufacturing Facility

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[redacted]

Prepared for:
Cameco Fuel Manufacturing Inc.

Prepared by:
Arcadis Canada Inc.
121 Granton Drive, Suite 12
Richmond Hill, ON, L4B 3N4

Tel (905) 764-9380
Fax (905) 764-9386

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1.0 INTRODUCTION

1.1 Background

Cameco Fuel Manufacturing Inc. (CFM, formerly Zircatec Precision Industries Inc.) owns and operates a nuclear fuel fabrication facility in Port Hope, Ontario. Cameco purchased the facility from Zircatec Precision Industries Inc. in 2006. CFM operates the facility under a licence from the Canadian Nuclear Safety Commission (CNSC), and is subject to the Nuclear Safety and Control (NSC) Act and Regulations. More detailed characterization of CFM is presented in Section 2.

Arcadis Canada Inc. (Arcadis) has been contracted to update the existing Environmental Risk Assessment (ERA) for the site, which was last prepared in 2006. This report contains the updated 2016 ERA for the CFM site.

1.2 Objectives of the Present Study

The objective of the present study is to complete an Environmental Risk Assessment (ERA) for the CFM facility, including Human Health Risk Assessment (HHRA) and Ecological Risk Assessment (EcoRA) in order to assess risks to human and non-human receptors from radiological and non-radiological contaminants related to current operations at the CFM facility, and, to account for:

(i) Newly acquired data from environmental monitoring and other studies;
(ii) Changes in ecological risk assessment guidance (e.g. publication of CSA N288.6 guidance on ERA [CSA 2012]); and,
(iii) Any potential changes to the CFM site or its surroundings since completion of the prior ERA in 2006.

The receptors in this HHRA are based on the most recent DRL (SENES 2011), and Cameco input, for consistency.

This ERA is based on data provided as of June 2015.

1.3 Report Organization

This report is structured as follows, based on the CSA (2012) recommended outline for ERAs:

Section 2.0 provides a characterization of the Site, including a description of the study area, engineered and natural environment, subsurface, and data currently available from monitoring programs and site investigations.

Section 3.0 describes modelling activities undertaken.

Section 4.0 presents the methodology and results of screening for contaminants of potential concern (COPCs).

Section 5.0 presents the Human Health Risk Assessment (HHRA), including selection of receptors, conceptual model for HHRA, methodology and results.

Section 6.0 presents the Ecological Risk Assessment (ERA), including selection of receptors, conceptual model for EcoRA, methodology and results.

Section 7.0 summarizes the conclusions and recommendations resulting from this study.

Many areas of uncertainty attend a risk assessment. This is due to the fact that assumptions have to be made throughout the assessment either due to data gaps, environmental fate complexities or in the generalization of receptor characteristics. To be able to place a level of confidence in the results, an accounting of the uncertainty, the magnitude and type of which are important in determining the significance of the results, must be completed. In recognition of these uncertainties, conservative assumptions were used throughout the assessment to ensure that the potential for an adverse effect would not be underestimated. In each of the major sections listed above, a sub-section describing uncertainty and conservatisms is provided.

2.0 SITE CHARACTERIZATION

2.1 Location, Boundaries, and Surroundings

The nuclear fuel fabrication facility is located in the Municipality of Port Hope (MPH), approximately 100 km east of Toronto (see Figure 2.1). The facility is located at 200 Dorset Street East, as shown in Figure 2.2. The operational facility and yards occupy part of Lot 2, Concession 1, Ward 1 of the Municipality of Port Hope, County of Northumberland and more specifically described in Instrument Number 89833 Parts 1 & 2 deposited in the Land Registry Office for the Registry Division of Port Hope, No. 9 on the 29th January, 1988.

The developed portion of the CFM site is approximately 4.1 hectares (ha) and is zoned Employment, General (formerly M-1 industrial). The licensed area is approximately half the developed area (2.3 ha), and excludes the parking lot areas. CFM also includes 12 ha of property to the north and east of the fenced perimeter of the plant. This land is also zoned as 'Employment, General' but has not been developed or used for any activity.

The facility is located northeast of the intersection between Rose Glen Road and Peter Street (formerly Highway No. 2) which links the MPH with the Town of Cobourg. The site is approximately 430 m from the north shore of Lake Ontario. The northern property limit is bounded by a Canadian Pacific Railway (CPR) right-of-way. The nearest residence is located immediately west of the site along Rose Glen Road. To the east of the site, the land is zoned 'Employment, General' and consists of mainly industrial/commercial buildings and land leased to local farmers. A commercial building is located on a small section of land southeast of the site.

Immediately to the south of the site, a triangular section of land bounded by Dorset Street East, Peter Street and Rose Glen Road is zoned as 'Parks'. To the south of Peter Street, the land is zoned 'Employment, General'. Two commercial facilities are located within approximately 70 m and 125 m of the southern edge of the site. Further to the southeast, the local municipal Sewage Treatment Plant is the only other facility located between the subject site and the north shore of Lake Ontario.

To the west of the site, a narrow strip of land is situated between the site and Rose Glen Road. This strip is zoned Low Density Residential, and is occupied by several privately owned homes and one private institution.

The plant is located on a slight topographic high, with the property generally sloping to the south east. Most of the property around the plant consists of a combination of hard surfaces (either concrete or asphaltic pavement) parking areas and access roads. Roads are drained to a combination of storm sewers and ditches, which discharge to a tributary of Gages Creek, located approximately 150 m to the east of the facility.

Figure 2.1 Location of Cameco Fuel Manufacturing Inc. (CFM)

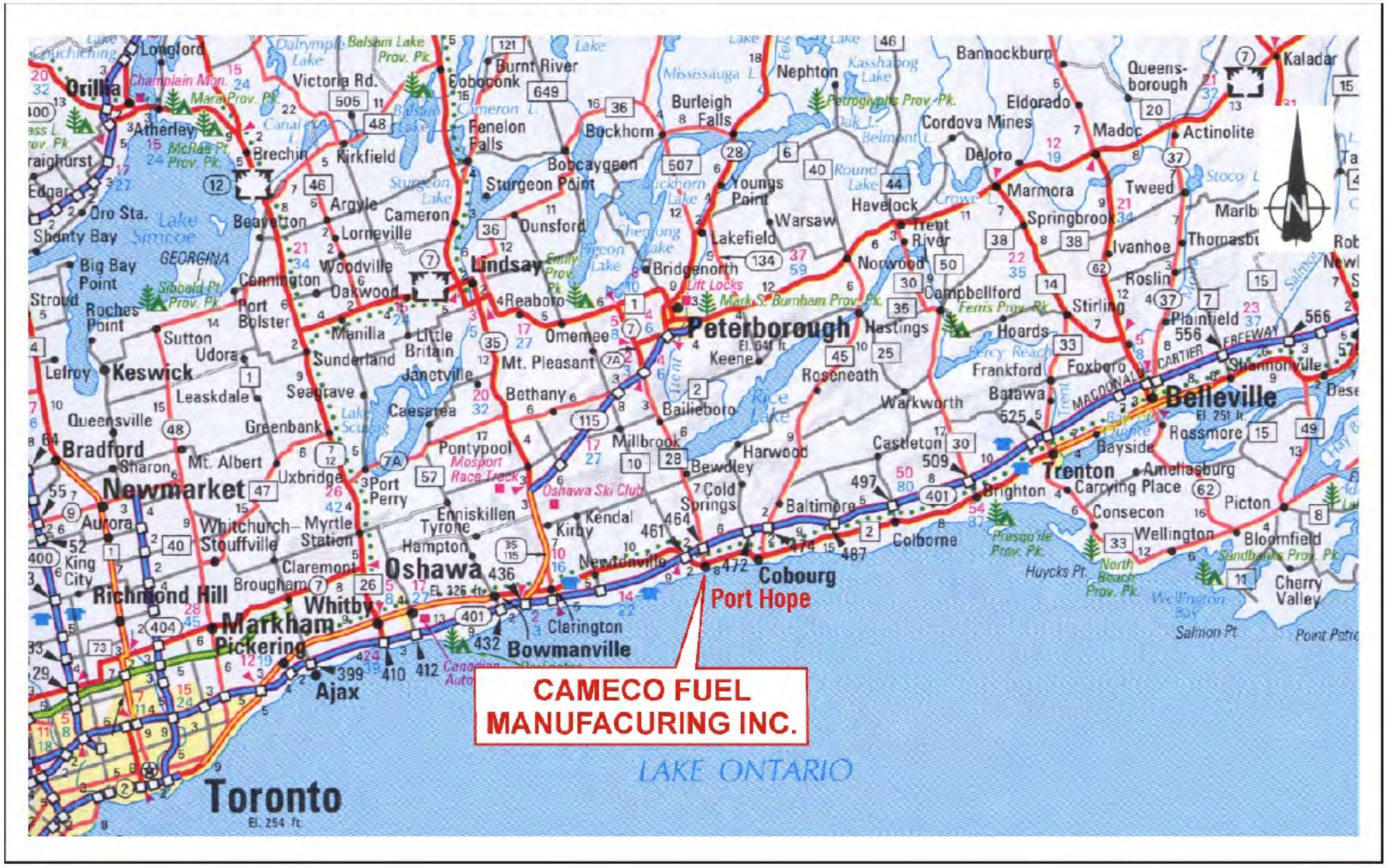


Figure 2.2 Cameco Fuel Manufacturing Inc. Site (CFM)

Source: Cameco (2015a)

2.1.1 Legal Description and Ownership

The legal description of the site was taken from the legal survey drawing prepared by Sylvester & Brown Engineering & Land Surveying (27 January 2011). The drawing indicates the legal description of the subject site is as follows:

Part of Lot 2, Concession 1, Ward 1, Municipality of Port Hope, County of Northumberland (described as Parts 1, 2, and 3 of Plan 9R 2776).

PIN: 51081 – 0036(LT)

Assessment Roll Number: 125080154000000

2.2 Site Operations

The CFM manufactures nuclear fuel, wherein powdered natural uranium in the form of uranium dioxide is pressed, sintered and ground into pellets, and loaded into Zircalloy tubes. The tubes are then welded to form a seal, and then welded into fuel bundles for shipment to CANDU nuclear generating stations.

The 200 Dorset Street East property is intended to be used by CFM for the foreseeable future. The CFM building will continue to function as a nuclear fuel fabrication facility.

2.3 Natural and Physical Environment

2.3.1 Subsurface Interpretation (Geology & Hydrogeology)

Lakefield, Aqua Terre and SLI have completed either detailed subsurface investigations and/or monitoring of the site and presented the information in several reports.

The subsurface stratigraphy of the site can be general summarized as follows:

- (0 to 2 m) – sand or sandy gravel fill
- (2 to 3 m) – silt or clay (silty clay)
- (3 to 4 m) – glacial drift (till)
- (5 to 7 m) – limestone (bedrock)

The porosity of the soil at the site is not available. Therefore, a total effective porosity of 0.481 for silty clay soil was assumed for the site (U.S. EPA 2004a).

The geology of the site (i.e. sand/gravel underlain by interbedded silty clay) gives rise to a shallow (at < 1.0 m bgs) perched water table. This system appears to be discontinuous and is likely fed by surface infiltration. A more permanent aquifer system is located in the deeper overburden, immediately above the bedrock. At this depth (4 to 6 m bgs), the glacial till contains more gravel and appears to exhibit high hydraulic conductivity.

In-situ testing i.e. bail tests conducted by Aqua Terre suggests that the overburden has a hydraulic conductivity on the order of 5×10^{-7} m/s and the bedrock hydraulic conductivity is quite variable ranging from $< 2 \times 10^{-7}$ m/s to $> 10^{-6}$ m/s.

Available data suggest that on a regional basis, groundwater generally flows to the south/southeast towards the groundwater collection system along the southern and eastern property boundaries. This observation is consistent with historical data. The localized influence of the pumping wells is evident in the majority of the monitoring wells (in both overburden and bedrock).

2.3.2 Terrestrial Ecological Environment

The CFM facility occupies the southern-most portion of the total site area. Within the CFM facility portion, the majority of the area consists of a combination of buildings and hard surfaces (either concrete or asphaltic pavement) including parking areas and access roads. North and east of the facility, the remaining area of the site contains a combination of landscaped natural area (lawns), as well as natural tree canopy. A small creek (Gages Creek) is located east of the CFM Facility. An agricultural field is located farther east of the site.

Immediately to the south of the site is a triangular section of land bounded on all sides by municipal roadways. This road median consists of primarily landscaped natural area. A similar section of land is located to the southeast of the facility, also containing some limited tree canopy.

Immediately west of the site is a strip of land containing public residences running parallel (north-south) with Rose Glen Road.

2.3.3 Aquatic Ecological Environment

Within the site boundary the aquatic environment is limited to that of Gages Creek, located to the east of the facility. The facility portion of the site (i.e. the built portion) does not support any aquatic or surface water features. The CFM site is located inland, approximately 430 meters north of the nearest Lake Ontario shoreline.

2.3.4 Meteorological Statistics and Climate Setting

Temperature

Temperature data for the past 5 years (January 2011 to December 2015) was obtained from the Environment Canada Climate Data website (http://climate.weather.gc.ca/) for the Cobourg STP station, deemed the most relevant local station, also used in the surface water modelling. Using this data, the following 5 year statistical temperature information was aggregated for the site:

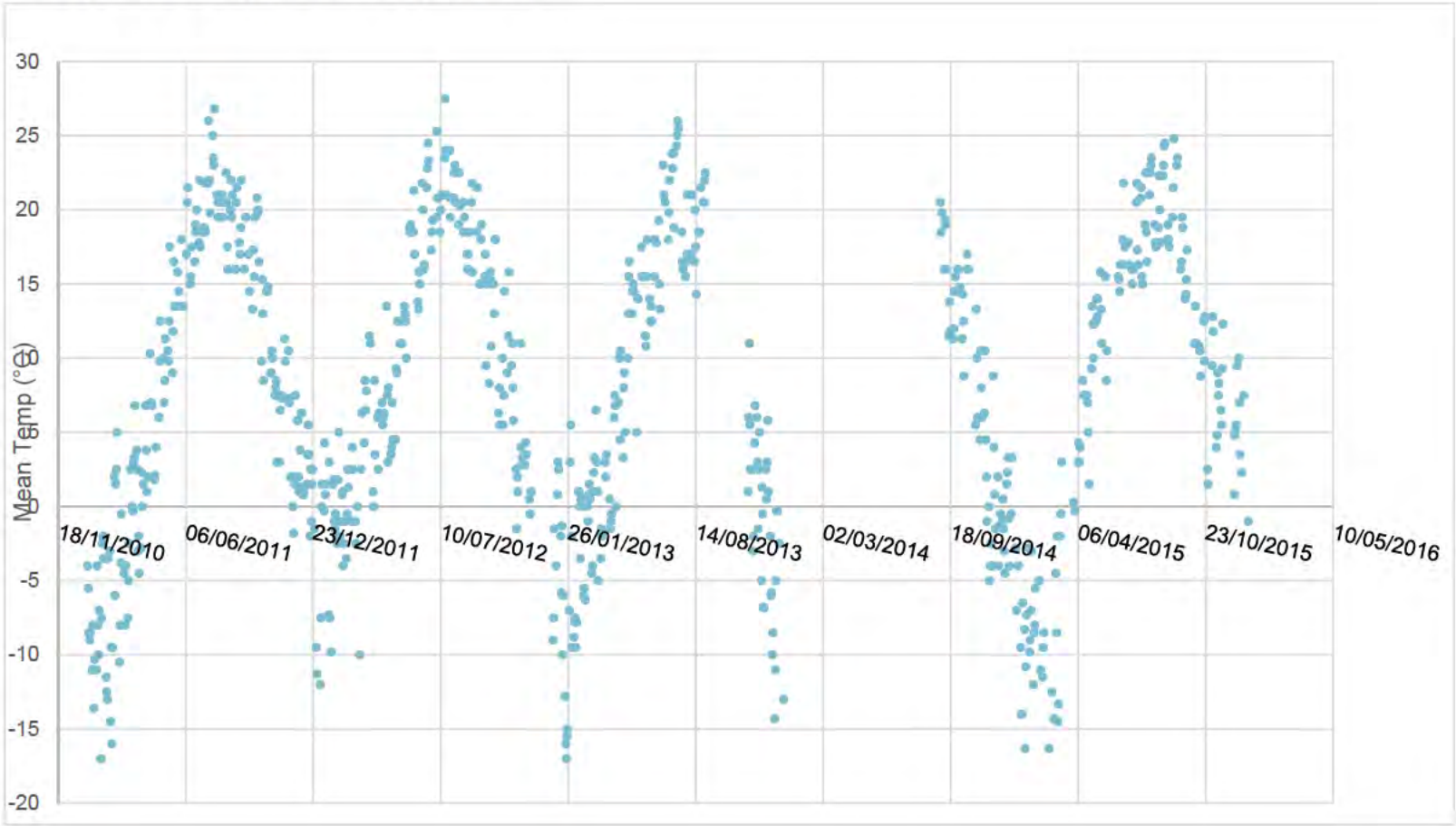
Min Daily Temperature: -26°C

Mean Daily Temperature: 7.7°C

Max Daily Temperature: 33°C

Mean daily temperatures for this time period are plotted in Figure 2.3.

Figure 2.3 Mean Daily Temperature (2011-2015)



Precipitation

Precipitation data for the past 5 years (January 2011 to December 2015) was obtained from the Environment Canada Climate Data website (http://climate.weather.gc.ca/) for the Cobourg STP station, deemed the most relevant local station, also used in the surface water modelling. Using this data, the following 5 year statistical precipitation information was aggregated for the site:

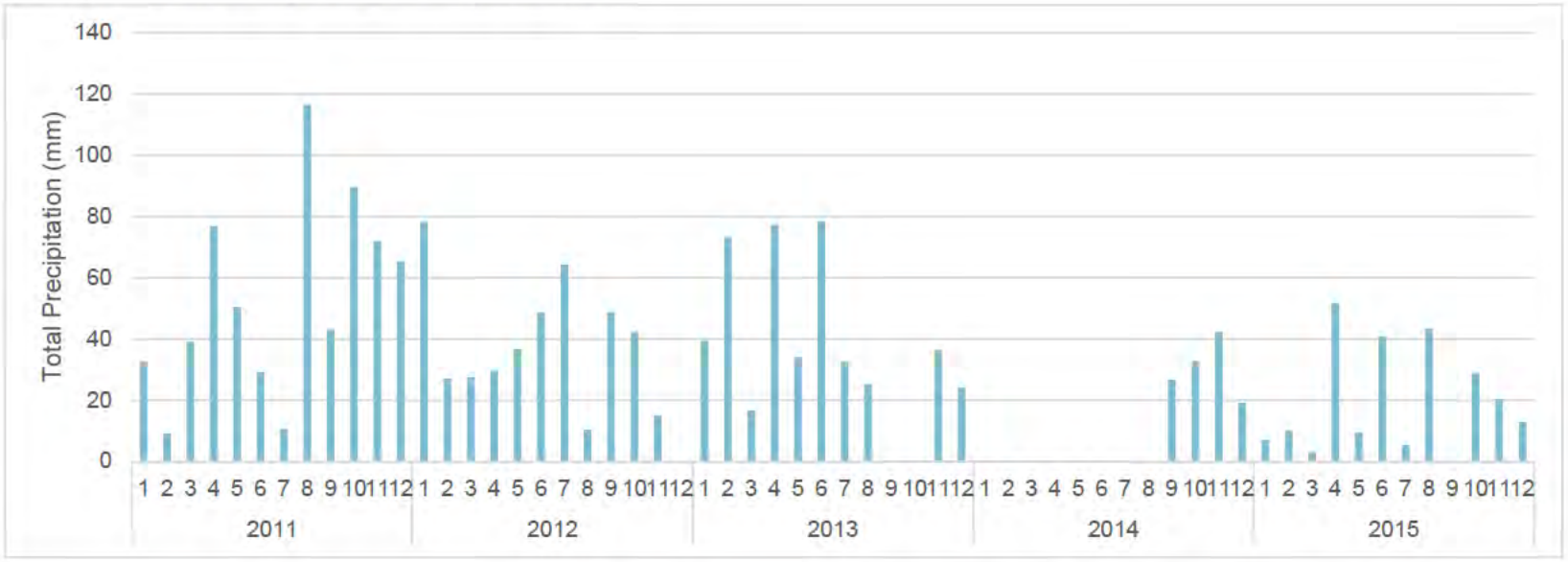
Min Annual Precipitation: 121 mm (2014)

Average Annual Precipitation: 370 mm

Max Annual Precipitation: 634 mm (2011)

Total monthly precipitation for this time period are plotted in Figure 2.4.

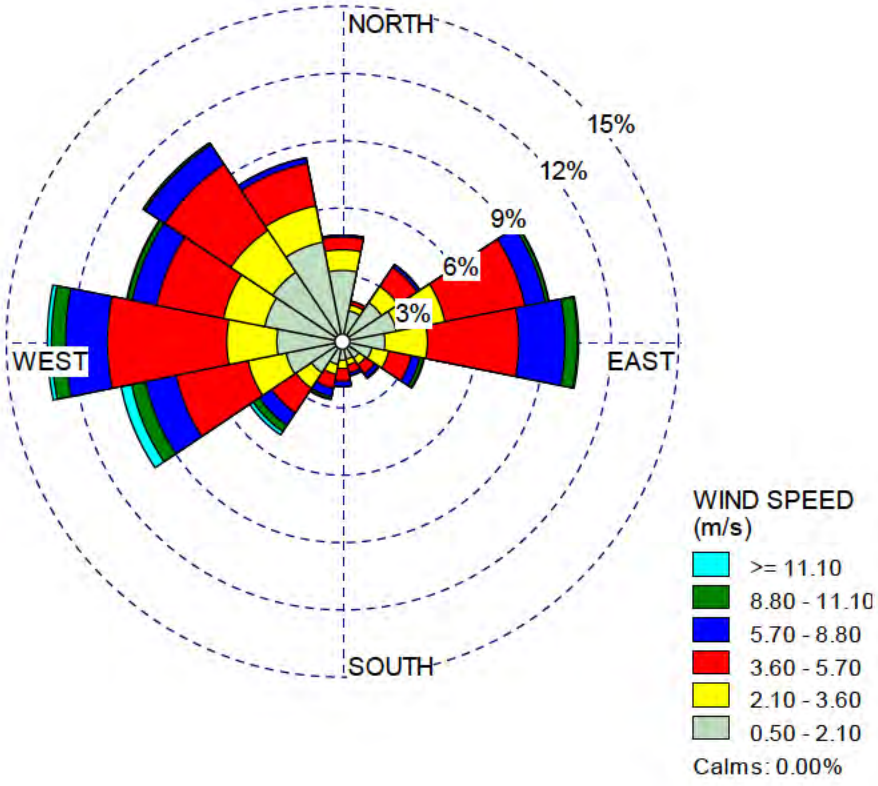
Figure 2.4 Total Monthly Precipitation (2011-2015)



Wind

For dispersion modelling, the long-term (five year) meteorological data set based on surface data from Cobourg and upper air data from Buffalo, New York (NY) was provided by the MOECC for the period 1997 to 2001. This was the previously processed meteorological data for the Port Hope CFM facility by the MOECC (with AERMET 06341) and then reprocessed with AERMET 14134 (by Arcadis) to use with the current regulatory version of AERMOD (i.e. version 14134). This meteorological data set was determined to be the most appropriate data set for modelling Port Hope CFM facility. The Cobourg meteorological station is located on the lakeshore and is at approximate distance of 9 km to the east from the CFM facility. The wind rose used for modelling in this assessment is shown in Figure 2.5. Winds occur most frequently from the west (W) direction. The overall average wind speed is approximately 3.4 m/s.

Figure 2.5 Wind Rose for Cobourg 1997-2001 Meteorological Data Set



Note: Wind directions shown are winds "blowing from"

2.4 Groundwater Contaminant Monitoring

Groundwater monitoring activities are conducted on-site and on properties located immediately adjacent and downgradient of the CFM plant, including properties owned by Rona, the MPH and Vosburgh Furniture. The monitoring well network currently consists of wells installed at six (6) interior (i.e. inside the plant) and seventy-two (72) exterior monitoring locations.

Uranium

The primary contaminant of concern (COC) under the CNSC license is uranium.

The SNC *2014 Groundwater Monitoring for Uranium Program* (SNC 2015a) is – at present - the most recent collection of groundwater data for the CFM site. Based on the results of groundwater monitoring and sampling conducted in 2014 (along with information from past years) SNC (2015a) provided the following observations:

- Uranium concentrations in groundwater in overburden were elevated in a relatively confined area on the site in the vicinity of the exterior of the northeast corner of the main building (TW-32-2 and TW-41-2). This corresponds to the area where elevated soil uranium concentrations were previously measured in shallow soil samples. It appears that the silt or clay unit across the site has largely reduced the potential vertical migration of uranium into bedrock.
- Uranium concentrations over time in selected monitoring wells were tabulated and presented in Appendix B of SNC (2015a). Significant trends were identified in the following wells:
    - TW-1 and TW-4 are significantly below the MOE Table 3 standard, but had slight increasing trends between 2008 and 2011. From 2011 onward, they appear to have a slight decreasing trend;
    - TW-6, TW-8-2, TW-10, TW-12, TW-37, TW-42 are significantly below the MOE Table 3 standard and have no discernible trend;
    - TW-8-3 has a slight decreasing trend, after a peak in 2004;
    - TW-20, TW-36, TW-39-1, TW-41-1 and TW-41-2 vary, with no discernible trend;
    - TW-43-2 is significantly below the MOE Table 3 standard, but from 2013 onward, has a slight increasing trend;
    - TW-32-2 has a decreasing trend, after a peak above the MOE Table 3 standard in 2008 and fluctuates above and below the criteria; and
    - TW-39-2 has a decreasing trend, after a peak in 2009.

According to SNC (2015a), based on available data, there is no evidence indicating off-site migration of uranium in groundwater.

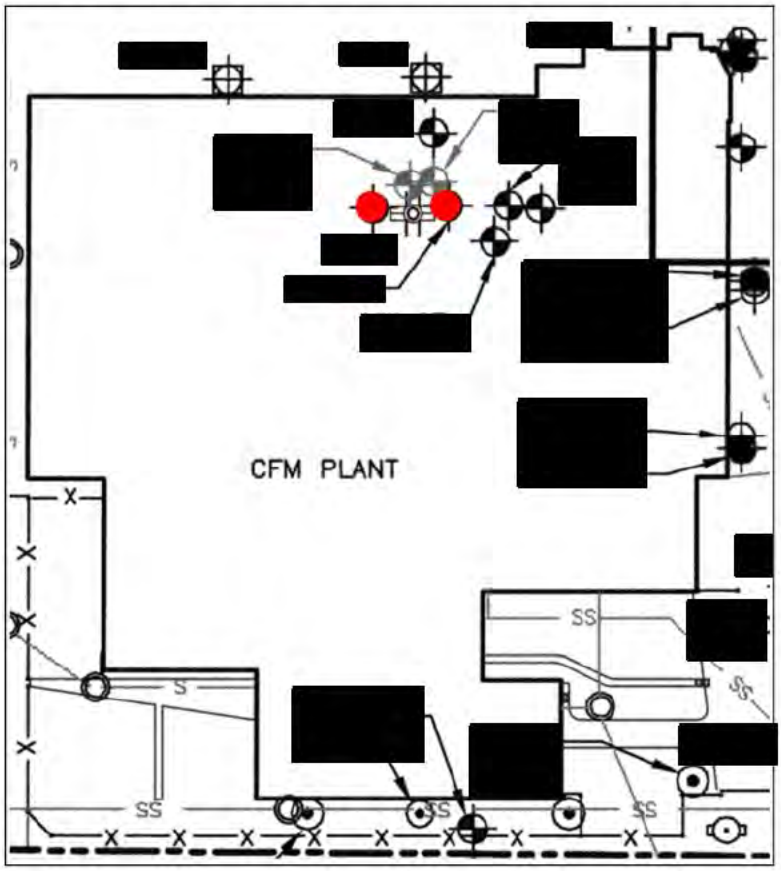
Trichloroethylene:

The primary COC at the site outside of the CNSC license is the chlorinated solvent trichloroethylene (TCE).

TCE was discovered in the subsoil adjacent to an underground neutralizing tank in 1993 between MW-1 and MW-2 (see Figure 2.6). The neutralizing tank and accessible impacted soil were removed in the summer of

1999. TCE can undergo either biotic or abiotic degradation in the natural environment. As part of this degradation process, various daughter products may be generated, including 1,1-dichloroethylene (1,1-DCE), cis-1,2-dichloroethylene (c-1,2-DCE), trans-1,2-dichloroethylene (t-1,2-DCE), and vinyl chloride (VC). Detectable concentrations of 1,1,1-trichloroethane (TCA) have also been reported during previous sampling events.

Figure 2.6 Underground Release of Trichloroethylene (TCE)



Note:
Red dots denote the approximate location of the TCE release into the subsurface beneath the CFM Plant

A groundwater pump and treat system was installed by SNC in 2000 at the CFM site. The system has been approved by the Ontario Ministry of the Environment (MOE) (Certificate of Approval #0832-4LJR8V) and is expected to operate for several years. The pump and treat system was installed to address TCE impacted groundwater at the site from three areas:

- southern and eastern property boundaries (12 pumping wells);
- interior pump and subsurface drain located in the former underground storage tank excavation; and
- groundwater drain located approximately 20 metres north of the plant.

The system began operation in November 2000. The installation of the treatment system and its operation from 2000 to 2007 were documented in previous annual reports (Aqua Terre, 2001, 2002, 2003, 2004, 2005a, 2006, 2007, 2008 and 2009). All annual reports have been submitted to the MOE. To mitigate the potential for environmental impacts on a nearby creek, the groundwater treatment system effluent has been discharging to the MPH sanitary sewer (an action level of 0.2 mg/L for uranium discharges to the MPH sanitary sewer is stated in the CFM operating license with the CNSC) since the spring of 2007. The treatment system effluent continues to meet the action level. In addition, CFM performs regular weekly testing at the sanitary sewer at the property line to demonstrate compliance.

2.5 Key Prior Risk Assessments & Environmental Studies

Environmental Review of the Zircatec Port Hope Fuel Fabrication Facility (2007)

The 2007 *Environmental Review* (SENES 2007) study was a radiological ERA for planned facility modifications by the prior site owner – Zircatec - to replace a portion of the natural uranium feed with slightly enriched uranium (SEU). The slight differences between the radiological characteristics of natural and SEU uranium were taken into account.

For humans, dose was evaluated for three types of human receptors: residents, nearby workers (non-Zircatec) and Zircatec Nuclear Energy Workers (NEWs). Pathways included inhalation and immersion in air; incidental ingestion of soil and groundwater; ingestion of backyard produce and fish; and municipal drinking water ingestion. The results indicated that all doses to residents and nearby workers due to Zircatec under current and future conditions and all production scenarios were below the CNSC dose limit of 1 mSv/y for members of the public. All estimated doses to all public receptors were below the limit of 1 mSv/yr; and nearly all were also below the *de minimis* dose of 10 μSv/y for members of the public.

For biota, the approach to estimating radioecological impacts was based on a high-level screening process. The doses to non-human biota calculated in this assessment include internal dose (i.e., through ingestion) and external dose from air, water and soil. The doses were then compared to the relevant Estimated No-Effect Values (ENEVs) by calculating the Risk Quotient (RQ) as the ratio of estimated dose to the ENEV. The results showed that all of the calculated RQ values for both aquatic and terrestrial biota were below one, indicating that no significant potential ecological effects are expected to non-human biota under both current and future conditions.

Derived Release Limits (2011)

The 2011 *Derived Release Limits* study (SENES 2011) characterizes human receptors and calculates derived release limits (DRLs) – both radiological and toxicological (non-radiological) - for facility emissions following the CSA N288.1 (2008) methodology. Facility releases of uranium to air, uranium in liquid effluents to the municipal sewer system, and gamma radiation from building inventories were included. Pathways included, but were not limited to, inhalation, incidental ingestion, and food ingestion. Overall, the resulting radiological DRLs for uranium were 22,000 kg/yr to water and 335 kg/yr to air; whereas the resulting toxicological DRLs for uranium were 523 kg/yr to water and 9.11 kg/yr to air.

Direct Gamma DRL Update (2014)

The 2014 Direct Gamma DRL study (SENES 2014) provides the direct gamma radiation dose and DRL calculations in support of Cameco's expansion of their existing Perimeter Gamma Monitoring program to account for the occupied second story portion of a new palliative care facility located near the north-west fenceline of the property in order to estimate and record the radiological dose to the most exposed member of the public (i.e. critical group).

The effective dose rates to residents of the new palliative care facility in the north-west location of the CFM site during calendar year 2013 were estimated using the measured ambient dose rates at the fenceline monitoring locations 101 and 102 and the ratios of the dose rates at the fenceline to the dose rate at the facility calculated using MicroShield (Grove Software 2012).

The annual dose to the average member of the Critical Group (infants) during 2013 was calculated to be 97 µSv at the new palliative care facility from direct gamma radiation. This calculation was based on annual effective dose rates (after subtracting controls and natural background) at monitoring location 101 at 0.14 µSv/h. Therefore, the DRL for direct gamma radiation was calculated to be:

- Annual average effective dose rate at TLD location 101 of 1 µSv/h.

This value is similar to the previous direct gamma DRLs of:

- Annual average effective dose rate at TLD location 1 of 0.35 µSv/h; and
- Annual average effective dose rate at TLD at all other locations of 1.18 µSv/h.

2.6 Available Environmental Data

The follow environmental data were included in this ERA.

2.6.1 Groundwater Quality Data

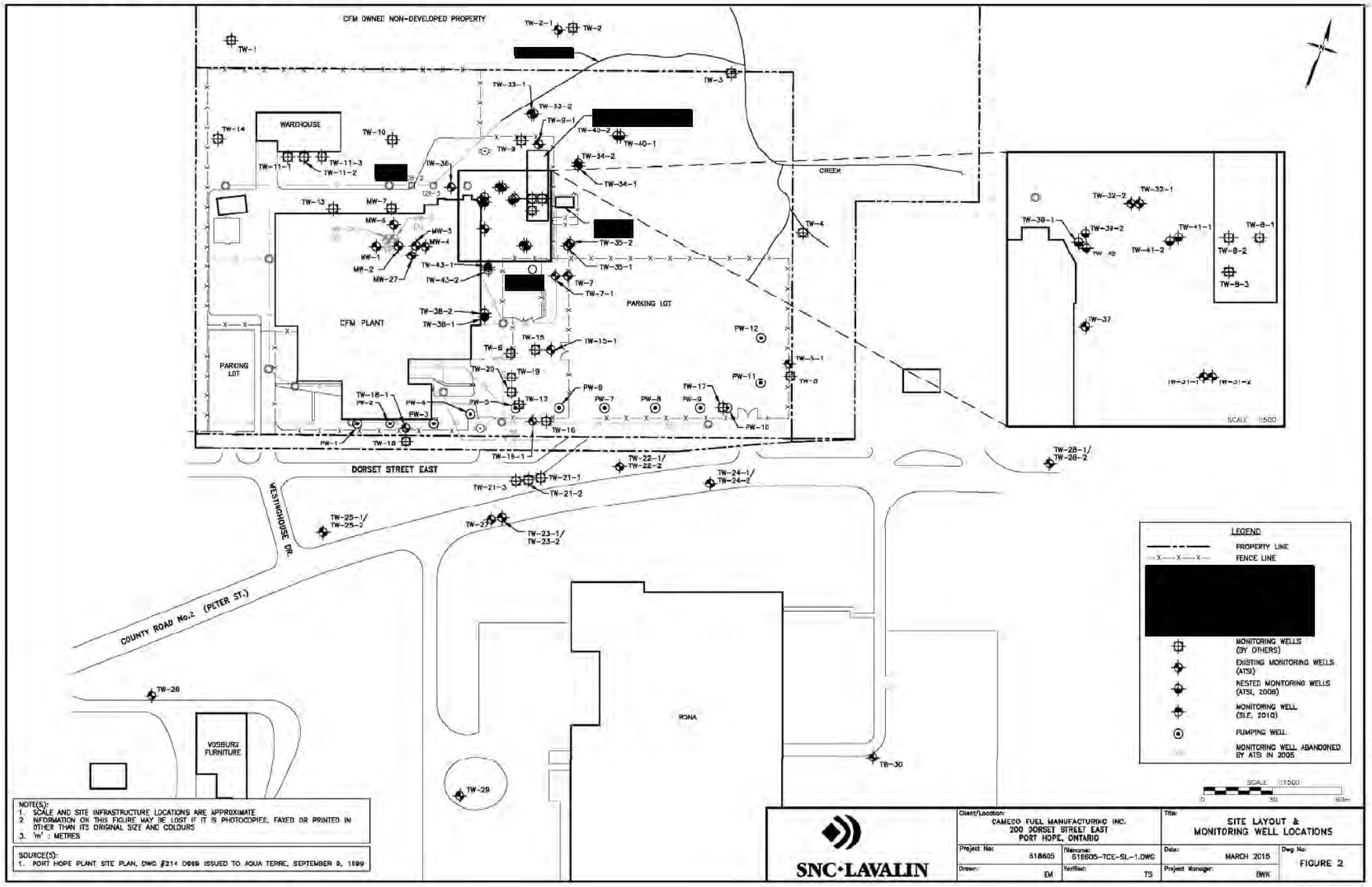
The 2014 groundwater quality data from CFM's ongoing groundwater monitoring program are used for this study. This data is documented in 2 reports, the first provides uranium concentrations, and the second provides VOC concentrations.

1. SNC 2015a: *2014 Groundwater Monitoring for Uranium Program – Port Hope, ON – Cameco Fuel Manufacturing.* March; and,
2. SNC 2015b: *2014 Summary of Remedial Activities – Port Hope, ON – Cameco Fuel Manufacturing.* March.

The 2014 groundwater quality data encompass the main contaminants related to site operations, including uranium, TCE, and TCE's degradation products.

The CFM groundwater monitoring program is illustrated in Figure 2.7.

Figure 2.7 Groundwater Monitoring Locations (SNC 2015a)



2.6.2 Soil Quality Data

Uranium soil quality data – for 2013 - from CFM's ongoing soil monitoring program are used in this study, along with 2009 VOC soil quality data from past interior soil sampling. This data is presented in 2 documents: the first provides uranium concentrations, and the second provides VOC concentrations.

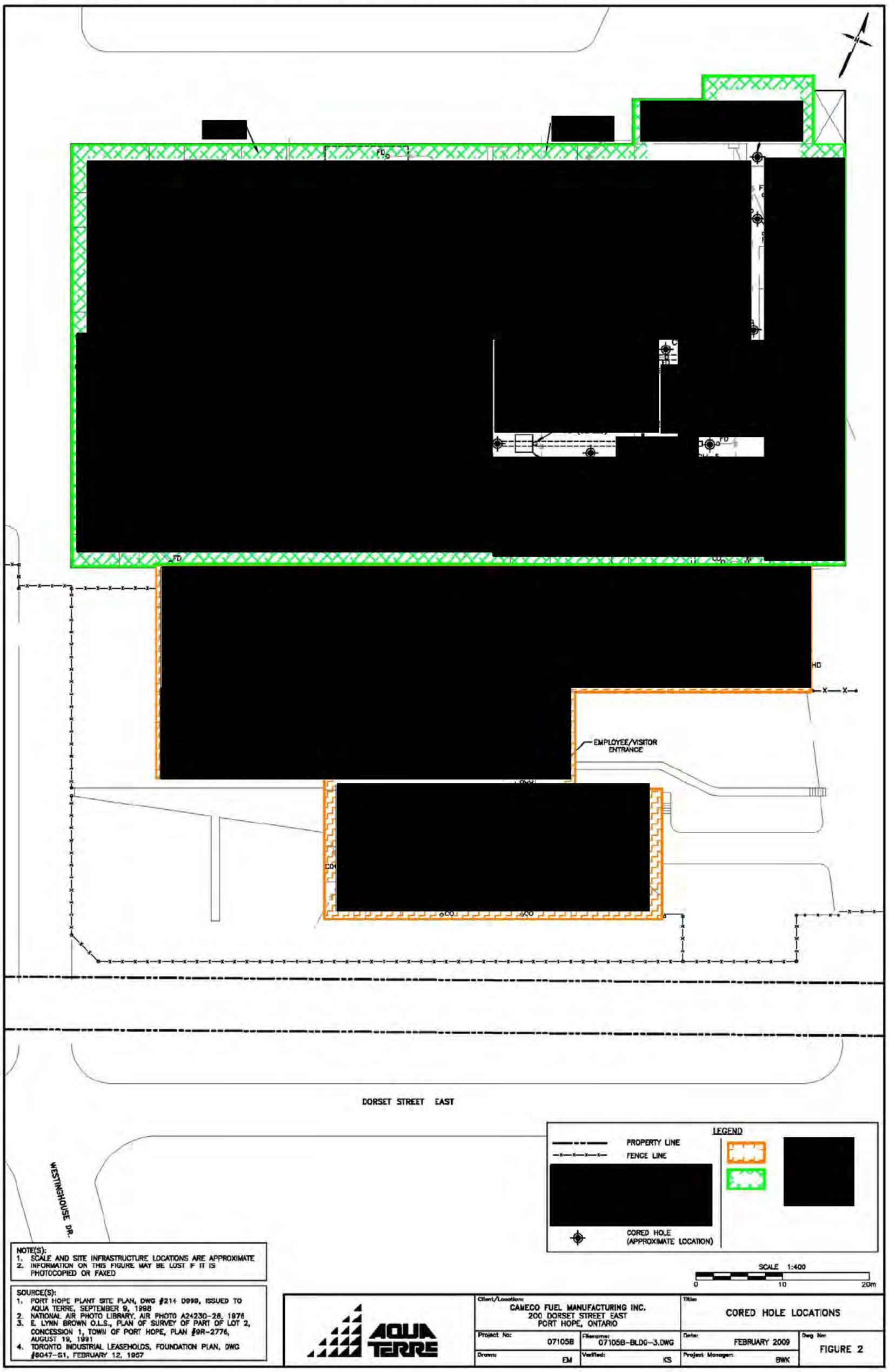
1. Cameco (2015a) *2014 Annual Compliance Monitoring & Operational Performance Report – Cameco Fuel Manufacturing.* March;

2. AquaTerre (2009) Letter to [redacted] *Interior Soil Sampling Program – VOCs – Final Report – Cameco Fuel Manufacturing.* March 3.

The soil quality data encompasses the most recent uranium sampling, which was performed in 2013, and the most recent VOC sampling, which was performed in 2008. The main contaminants related to site operations are uranium, TCE, and TCE degradation products.

Soil VOC sampling locations from the AquaTerre (2009) study are illustrated in Figure 2.8.

Figure 2.8 Soil Sampling Locations – Volatile Organic Compounds (Aqua Terre 2009)



2.6.3 Surface Water Quality Data

The 2014 surface water quality data from the CFM ongoing environmental monitoring program are used in this study. This data is presented in 2 documents: the first provides uranium concentrations, and the second provides VOC concentrations.

- SNC 2015a: *2014 Groundwater Monitoring for Uranium Program – Port Hope, ON – Cameco Fuel Manufacturing.* March;

- SNC 2015b: *2014 Summary of Remedial Activities – Port Hope, ON – Cameco Fuel Manufacturing.* March.

The CFM surface water monitoring program locations are shown in Figure 2.9.

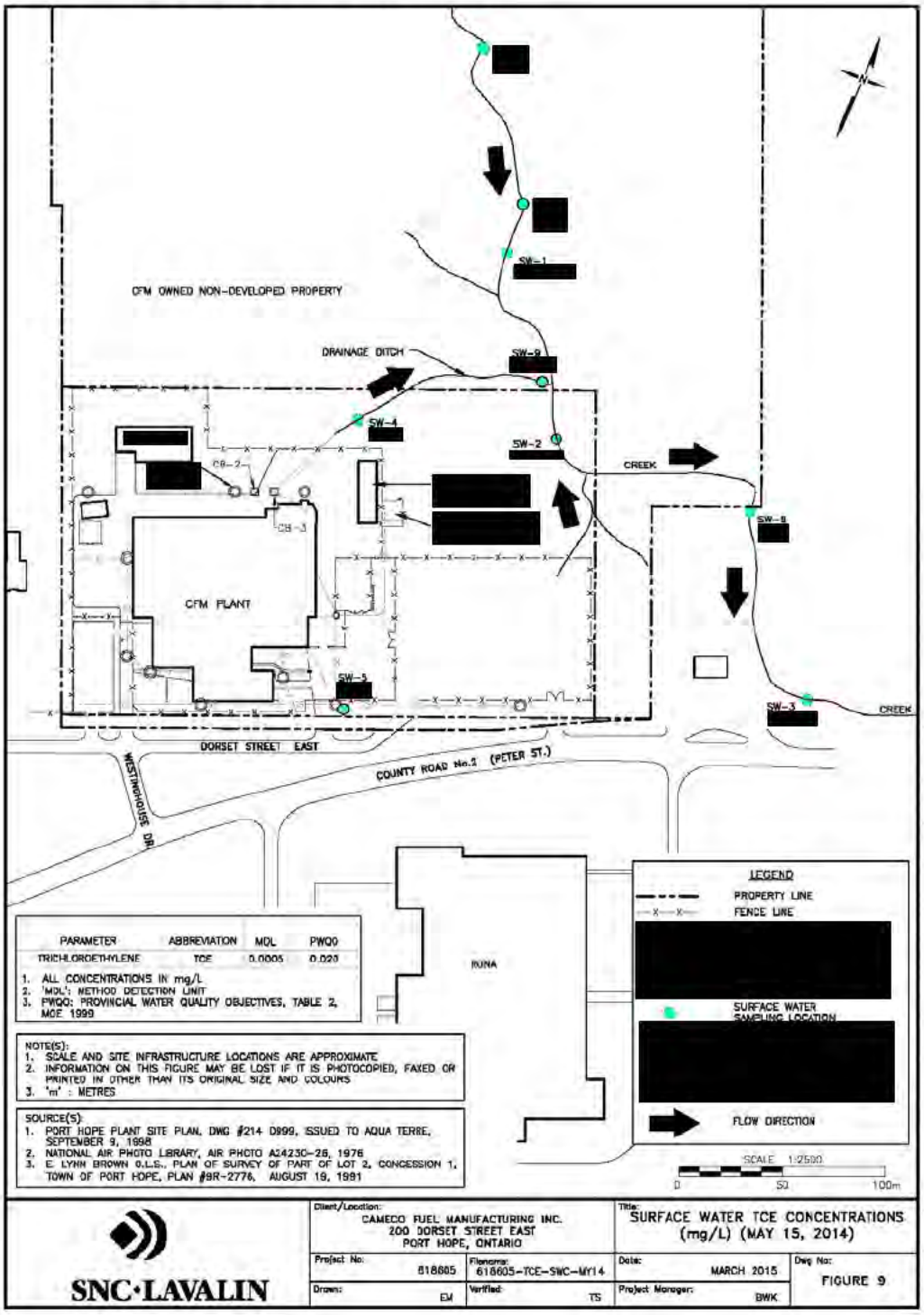
Surface water quality data encompasses two main locations (as shown in Figure 2.9):

1. Drainage Ditch – flows from the facility to Gage's Creek and

2. Gage's Creek – flows from north of the facility, across the facility property and then south east.

The 2014 surface water quality data encompass the main contaminants related to site operations, including uranium, TCE, and TCE degradation products.

Figure 2.9 Surface Water Sampling Locations



2.6.4 Sediment Quality Data

The 2014 sediment uranium concentration data from the CFM ongoing environmental monitoring program are used in this study. This data is presented the following document, for uranium only.

1. SNC 2015a: *2014 Groundwater Monitoring for Uranium Program – Port Hope, ON – Cameco Fuel Manufacturing.* March.

For this assessment, only 2014 data was used. Sediment sampling locations are the same as surface water locations. See Figure 2.9 above.

2.6.5 Outdoor Air Quality Data

The air quality data considered in this study and used in the air dispersion modelling were supplied by Cameco, as follows:

- the uranium emissions from the process stacks were based on 2014 maximum annual stack testing results provided by Cameco;
- the uranium emissions from building ventilation were assessed from releases of particulate UO_2 to air from building ventilation from the facility. The estimated release of UO_2 from exhaust ventilation during 2014 was 0.40 kg (Cameco, 2015a);
- a total of 26 stacks were modelled as sources of uranium emission in this assessment. Source characteristics (e.g., stack height, stack diameter, flow rate, etc.) and building configurations were provided by Cameco.

2.6.6 Indoor Air Quality Data

Routine in-plant air sampling is conducted throughout the plant continuously during operations to monitor airborne UO2 in the work environment and this study uses the 2014 results from the recent CFM annual compliance report (Cameco 2015a).

2.6.7 Discharge (Liquid Effluent) Quality Data

Data characterizing uranium in liquid effluents from the CFM facility are available from the recent CFM annual compliance report (Cameco 2015a).

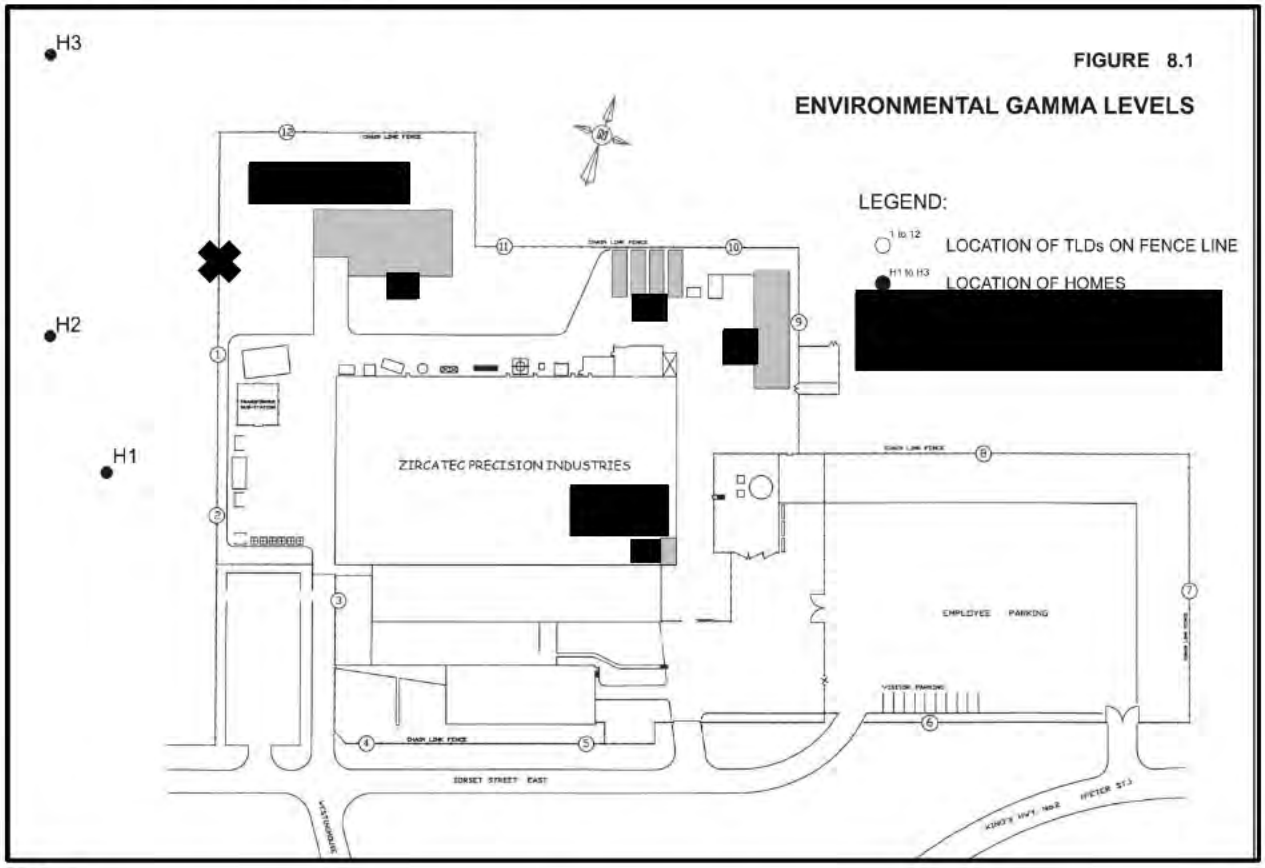
It is important to note that this data represents liquid effluents released by the CFM facility *into the municipal sewer system*, and not to the environment directly. Effluents released to the municipal sewer system are received by the Port Hope Sewage Treatment Plant (STP), where they are combined with effluents from other sewer users and undergo municipal sewage treatment processes before being released to Lake Ontario via the submerged municipal offshore diffuser.

2.6.8 Gamma Measurement Data

Fenceline gamma measurement data as well as in-plant gamma measurement data from 2014 are used in this study. Gamma measurement data are obtained from the Cameco (2015a) 2014 compliance report. Cameco measures gamma levels in several locations at the CFM facility, including along the facility fenceline.

Figure 2.10 illustrates the locations of the fenceline gamma monitoring locations.

Figure 2.10 Gamma Monitoring Locations



Notes:

✖ indicates new fenceline gamma Station 101 / 102 (new as of Q1 2014, SENES 2014)

2.6.9 Radionuclide Data

Radionuclide measurement data are not obtained as part of the regular CFM environmental monitoring program. Instead, radionuclide concentrations were estimated by correlating measured uranium concentrations – which are included as part of CFM's monitoring programs – to the corresponding levels of U-234, U-235 and U-238 isotopes using specific activity conversions (Lowe 2004).

2.7 Uncertainties in Site Characterization

Due to the large number of environmental studies conducted by Cameco, the site is well-characterized and there are few uncertainties or data gaps with respect to site description. The only major uncertainty identified is the limited selection of radionuclide measurement data. As discussed in Section 2.6.9 above, in the absence of radionuclide measurements, the levels of U-234, U-235 and U-238 were estimated based on measured uranium concentrations. *Degree of uncertainty: Medium*

3.0 MODELLING

3.1 Modelling Air Releases

In 2016, Arcadis carried out air dispersion modelling of uranium emissions from the Port Hope CFM, using the AERMOD dispersion model, to determine annual average air concentrations and deposition rates. Concentrations and deposition rates were estimated for both the standard Ontario Ministry of Environment and Climate Change (MOECC) model receptor grid as well as discrete receptor locations. Discrete receptor locations were defined along the facility fenceline and at additional four risk receptors to estimate human impacts. The results predicted at discrete receptor locations were provided as inputs to the present risk assessment.

The air dispersion modelling was completed in accordance with the MOECC document "Air Dispersion Modelling Guideline for Ontario (ADMGO), Version 2.0" dated March 2009. [redacted] The modelling results are summarized briefly below.

3.1.1 Sources

A total of 26 stacks were modelled as sources of uranium emission in this assessment. Source characteristics (e.g., stack height, stack diameter, flow rate, etc.) and building configurations were provided by Cameco. The emission rates from the point sources used to estimate the annual average predicted air concentrations were determined from measured releases from the stacks.

Air dispersion modelling was carried out based on 2014 uranium emission rates from the CFM facility. The uranium emissions from the process stacks were based on 2014 maximum annual stack testing results provided by Cameco. The uranium emissions from building ventilation were assessed from releases of particulate UO_2 to air from building ventilation at the facility.

3.1.2 Receptors

Receptors were chosen based on recommendations provided in Section 7.1 of the ADMGO. Specifically, a nested receptor grid, centered on the emissions sources was used. Receptors were also placed every 20 metres along the property line. In addition to the MOECC grid, discrete sensitive receptors were also included in the model. The model results predicted at this group of receptors were provided as inputs to this risk assessment.

Discrete receptors were also placed at the locations of the Hi-Volume air samplers. CFM uses hi-volume air samplers to measure the concentrations of UO_2 at the four corners within the CFM fence line. Model results predicted at these monitoring locations were used for model validation (see Section 3.1.5).

3.1.3 Model Results

Model predicted annual average uranium concentrations across the modelling domain are presented in Figure 3.1. All concentrations are below the annual average standard/criterion of 0.03 µg/m³ (in PM_{10}) (MOECC, 2012). The highest predicted concentration is 0.0012 µg/m³ at 4% of the uranium standard. As can be seen in Figure 3.1, the overall maximum uranium concentration is located along the north-eastern portion of the fenceline, in close proximity to the stacks sources of uranium release (green triangle marker).

In addition, Table 3.1 shows the model predicted uranium concentrations at each of the risk receptor locations.

Table 3.1 Model Predicted Average Annual Uranium Concentrations (µg/m³) at the Risk Receptors

Receptor	Location Type	Easting	Northing	Annual Average Concentration (µg/m³)
Maximum	Fenceline receptor	718715	4870448	0.00122
N1	North Side Fenceline Receptor	718546	4870469	0.00022
N8	North Side Fenceline Receptor	718660	4870513	0.00029
N9	North Side Fenceline Receptor	718670	4870487	0.00053
N11	North Side Fenceline Receptor	718698	4870498	0.00035
E6	East Side Fenceline Receptor	718707	4870474	0.00067
N12	East Side Fenceline Receptor	718716	4870477	0.00049
E5	East Side Fenceline Receptor	718721	4870466	0.00063
E4	East Side Fenceline Receptor	718710	4870462	0.00093
N19	North Side Fenceline Receptor	718812	4870485	0.00031
S14	South Side Fenceline Receptor	718837	4870421	0.00037
S6	South Side Fenceline Receptor	718705	4870370	0.00110
S5	South Side Fenceline Receptor	718706	4870365	0.00099
W1	West Side Fenceline Receptor	718632	4870335	0.00047
W2	West Side Fenceline Receptor	718624	4870343	0.00053
W3	West Side Fenceline Receptor	718614	4870338	0.00045
W5	West Side Fenceline Receptor	718601	4870372	0.00095
W6	West Side Fenceline Receptor	718584	4870365	0.00072
N2	North Side Fenceline Receptor	718562	4870476	0.00022
N3	North Side Fenceline Receptor	718578	4870482	0.00022
N4	North Side Fenceline Receptor	718595	4870488	0.00024
N5	North Side Fenceline Receptor	718611	4870494	0.00026
N6	North Side Fenceline Receptor	718627	4870500	0.00029
N7	North Side Fenceline Receptor	718644	4870507	0.00029
E8	East Side Fenceline Receptor	718665	4870500	0.00034
N10	North Side Fenceline Receptor	718684	4870492	0.00044

Receptor	Location Type	Easting	Northing	Annual Average Concentration (µg/m³)
E7	East Side Fenceline Receptor	718702	4870486	0.00043
N14	North Side Fenceline Receptor	718731	4870454	0.00073
N15	North Side Fenceline Receptor	718747	4870460	0.00059
N16	North Side Fenceline Receptor	718763	4870466	0.00048
N17	North Side Fenceline Receptor	718780	4870473	0.00041
N18	North Side Fenceline Receptor	718796	4870479	0.00036
E3	East Side Fenceline Receptor	718818	4870469	0.00034
E2	East Side Fenceline Receptor	718824	4870453	0.00036
E1	East Side Fenceline Receptor	718830	4870437	0.00036
S13	South Side Fenceline Receptor	718820	4870415	0.00042
S12	South Side Fenceline Receptor	718804	4870408	0.00050
S11	South Side Fenceline Receptor	718787	4870402	0.00057
S10	South Side Fenceline Receptor	718771	4870396	0.00065
S9	South Side Fenceline Receptor	718754	4870389	0.00074
S8	South Side Fenceline Receptor	718738	4870383	0.00083
S7	South Side Fenceline Receptor	718721	4870377	0.00099
S4	South Side Fenceline Receptor	718691	4870359	0.00117
S3	South Side Fenceline Receptor	718676	4870353	0.00099
S2	South Side Fenceline Receptor	718661	4870347	0.00076
S1	South Side Fenceline Receptor	718646	4870341	0.00059
W4	West Side Fenceline Receptor	718608	4870355	0.00066
W7	West Side Fenceline Receptor	718578	4870382	0.00098
W8	West Side Fenceline Receptor	718571	4870400	0.00099
W9	West Side Fenceline Receptor	718565	4870417	0.00063
W10	West Side Fenceline Receptor	718559	4870435	0.00042
W11	West Side Fenceline Receptor	718552	4870452	0.00030
R1	Commercial Off-Site Worker	718850	4870277	0.00029
R2	Maintenance Off-Site Worker	718875	4870466	0.00025
R3	Sub-surface Off-Site Worker	718715	4870448	0.00122
R4	Resident	718548	4870378	0.00048

Figure 3.1 Annual Average Uranium Concentrations (µg/m^3)

▲ - Location of maximum concentration

3.1.4 Calculation of Deposition Velocity

To determine the deposition rates of uranium within the modelling domain, a deposition velocity needs to be calculated and applied to the model predicted uranium concentrations. A deposition velocity is usually calculated using monitoring data from hi-volume particulate samplers co-located with dustfall jars. There is no dustfall monitoring data at the Port Hope CFM facility, and a deposition velocity of 4.4 cm/s calculated for the nearby Port Hope Conversion facility (Arcadis 2016) was used to determine the deposition rate at CFM.

3.1.5 Comparison: Model vs. Monitoring Data

To evaluate the performance of the model, predicted concentrations are compared to monitoring data. A model is considered to perform well if the model results are within a factor of 2 of observed values (U.S. EPA, 2003). The comparison of AERMOD predicted concentrations with the CFM 2014 Hi-vol monitoring data is shown in Table 3.2. Predicted uranium concentrations are within a factor of 3 to 10 of monitored data. The emission rates from the process stacks used in this modelling assessment were conservatively based on maximum annual stack testing results for 2014. In addition, the modelling approach that assumes emissions from the stacks to occur for every hour of the modelling period and at the same rate for each hour in the year, also contributes to the conservative prediction of annual uranium concentrations.

Table 3.2 Comparison of Modelled vs. Monitored Uranium Concentrations

Hi-Vol Monitoring Station	UTM Coordinates		Annual Concentration (µg/m^3)		
	Easting (m)	Northing (m)	Observed-2014	AERMOD	Ratio Mod/Obs.
Hi-Vol Station -South West	718627	4870344	7.60E-05	7.29E-04	10
Hi-Vol Station -East	718805	4870478	9.20E-05	4.25E-04	5
Hi-Vol Station -North	718678	4870486	9.70E-05	6.94E-04	7
Hi-Vol Station -North West	718555	4870464	1.20E-04	3.20E-04	3

3.2 Soil Deposition & Build-Up

Measured concentration data are not available for offsite soils, however, offsite soil levels are needed for later risk calculations. Therefore, there is a need to estimate offsite soil concentrations using a predictive model.

3.2.1 Soil Characteristics for Modelling

In 2008, SENES (now Arcadis) conducted a detailed soil characterization study throughout the Port Hope area. The SENES (2008) study provides location-specific soil parameters for several soil sites, and provides a predictive soil model for estimating uranium concentrations in soil. In relation to the CFM facility, the closest SENES (2008) soil site is location '3-8-A', located nearby at the northwest corner of the intersection of Peter Street and Rose Glen Road.

3.2.2 Soil Modelling Methodology

Incremental soil concentrations - representing the amount of uranium accumulated annually as a result of emissions from CFM - were estimated using site-specific soil parameters measured from location 3-8-A, fenceline air concentrations from Table 3.1.

The method for soil modelling is based on air dispersion modelling, measured deposition velocities and a physical soil model that incorporates loss mechanisms due to leaching process. The predicted soil concentration is also influenced by current measured soil concentrations, however, the present study requires incremental soil concentration for current and future releases and therefore uses an initial soil concentration of zero.

Initial Soil Concentration

As discussed above, the present study requires incremental soil concentration based on current and future releases. As such, the initial starting soil concentration or 'base soil concentration' is assumed to be zero so that the incremental contribution to soil from CFM emissions can be estimated.

Deposition Rate

Deposition rates were calculated by multiplying the modelled air concentrations by the settling velocity (deposition velocity). As discussed in Section 3.1.4, there is no dustfall monitoring data at the CFM facility at Port Hope, and a deposition velocity of 4.4 cm/s calculated for the nearby Port Hope Conversion facility (Arcadis 2016) was used to determine the deposition rate at CFM.

Modelling Soil Removal Processes

The soil concentrations resulting from air deposition depend on the deposition rate, the duration of deposition and natural mechanisms that remove uranium from the soil. Uranium is naturally removed from the soil by many mechanisms including soil erosion, leaching and surface run-off. For this study, the only mechanism considered for removal is leaching.

The soil loss constant of uranium from the soil due to leaching may be calculated using the following equation described in U.S. NCRP (1984):

$$k_{leaching} = \frac{V_w}{d_s\left[1+\left(\frac{\rho}{\Theta}K_{Di}\right)\right]} \times 365$$

where:

$k_{leaching}$	=	soil loss coefficient due to leaching (1/yr)
V_w	=	velocity of water percolation downward through soil (cm/d)
d_s	=	depth of soil zone of interest (cm)
ρ	=	bulk soil density (g/cm^3)

Θ = soil water content (mL/cm^3)
K_D = equilibrium distribution coefficient (mL/g)
365 = conversion from 1/d to 1/yr

Predicting Soil Concentrations (Accumulation & Removal)

Soil concentrations over the time period were estimated on a year-by-year basis using the following equation:

$$C_{soil}(t) = \left(C_{soil}(t-1) + \frac{D(t)}{d_s \times \rho} \right) e^{-k}$$

where:

$C_{soil}(t)$ = soil concentration at time (t) (µg/g or mg/kg)
D(t) = uranium deposition rate (µg/(cm^2 yr))
d_s = soil mixing depth (cm)
ρ = bulk soil density (g/cm^3)
k = soil loss coefficient due to leaching (1/yr) *[calculated, as above]*

Table 3.3 Soil Modelling: Parameter Values

Input Parameter	Description	Units	Value	References & Comments
V_w	Velocity of water percolation through soil	cm/d	0.066	CSA N288.1 (2014): Default value for southern Ontario soils
D_s	Depth of soil zone of interest - surface	cm	2.5	Assumed; consistent with MOE (1996)
ρ	Soil bulk density	g/cm^3	1.277	SENES 2008; measured value (location-specific)
Θ	Soil water content	mL/cm^3	0.1354	SENES 2008 measured value (location-specific)
K_D	Equilibrium distribution coefficient	mL/g	76	SENES 2008 measured value (location-specific)
V_{dep}	Deposition velocity	cm/s	4.4	(Arcadis 2016) from nearby Port Hope Conversion Facility
C_{air}	Uranium concentration in air	µg/m^3	0.00122	maximum modelled fenceline air concentration (Table 3.1)
D(t)	Uranium deposition rate	µg/(cm^2 y)	0.169	$=C_{air}*V_{dep}/100*3600*24*365/100^2$
$K_{leaching}$	Soil loss constant from leaching - surface	1/yr	0.0134	Calculated, as discuss above.

Soil concentrations were calculated for each time period assuming that the incremental concentration at the beginning of the time period was zero. The concentration at the end of the time period is used as the predicted uranium concentrations for estimating dose.

3.2.3 Soil Modelling Results

The resulting incremental soil concentration is presented in Table 3.4; detailed soil modelling calculations are available in Appendix B.

Table 3.4 Off-Site Soil Modelling and Results

Monitoring Station	U-in-Air Concentration (µg/m^3) (Table 3.1)	Modelled Incremental Soil U Concentration (µg/g) *[2.5 cm surface depth]*
The nearest soil location for which soil parameter values are available is location 3-8-A. It is used preferentially because it is located in close proximity to the CFM facility (across the street).	0.00122	0.05

3.3 Soil & Groundwater Vapours to Trench-Air

Volatile contaminants in soil or groundwater are capable of migrating upward, through overhead soil layers or cracks in building foundations, and entering the air above. This is referred to as vapour intrusion.

Later HHRA calculations require the estimation of vapour concentrations in air contained within a subsurface trench (e.g. a trench dug for the installation or maintenance of underground utilities). In order to estimate trench-air concentrations from vapour migration, the following methods were use:

- *Vapours from Groundwater:* To calculate the concentration of vapour migrating up from *groundwater*, the ASTM (1995) methodology for estimating vapour intrusion to outdoor air is used, in combination with reduced wind speed to better represent stagnant air conditions within a subsurface trench protected from wind.
- *Vapours from Soil:* In order to estimate trench-air concentrations from vapours migrating up from *soil*, the OMOE (2011) methodology for estimating vapour intrusion to outdoor air is used, in combination with reduced wind speed to better represent stagnant air conditions within a subsurface trench protected from wind.

These are discussed separately in the following subsections. [redacted]

3.3.1 Estimating Vapours from Groundwater: ASTM 1995

Overall, the ASTM 1995 methodology calculates vapour concentrations by multiplying the concentration in groundwater, by a derived 'Volatilization Fraction' (VF). Calculations are as follows:

$$C_{vap} = C_{gw} \times VF$$

Where,

C_{cap} = Vapour concentration (mg/m^3)
C_{gw} = Groundwater concentration (mg/L)
VF = see below

$$VF = \frac{H'}{1 + \left[\frac{U_{air} \delta_{air} L_{gw}}{W \; D_{eff,ws}} \right]}$$

Where,

VF = Volatilization Fraction (in mg/m$^3_{air}$ per mg/L$_{groundwater}$)
H' = see below
U_{air} = Wind speed (in cm/s)
δ_{air} = height of mixing cell (in cm)
L_{gw} = depth to groundwater/water table (in cm)
W = length of source zone (in cm)
$D_{eff,ws}$ = see below

Of these inputs, H' and $D_{eff,ws}$ are calculated using separate equations:

$$H' = \frac{H}{R \times T}$$

Where,

H = Henry's law coefficient (in Pa•m^3/mol)
R = universal gas constant (8.314 atm•m^3/mol•K)
T = Temperature (in °Kelvin)

$$D_{eff,ws} = \frac{(h_{cap} + h_v)}{\left[\frac{h_{cap}}{D_{cap}} + \frac{h_v}{D_{eff,s}} \right]}$$

Where,

$D_{eff,ws}$ = Effective diffusion coefficient between groundwater and soil surface (in cm^2/s)
h_{cap} = Thickness (height) of capillary fringe (in cm)
h_v = Thickness (height) of vadose zone (in cm)
D_{cap} = see below
$D_{eff,s}$ = see below

Of these inputs, D_{cap} and $D_{eff,s}$ are calculated using separate equations:

$$D_{cap} = [D_a \times \frac{\theta_{acap}^{10/3}}{\theta_t^2}] + [D_w \times \frac{\theta_{wcap}^{10/3}}{H \times \theta_t^2}]$$

Where,

D_{cap} = Effective diffusion coefficient through capillary fringe (in cm^2/s).
D_a = Gas diffusion coefficient (in cm^2/s) [varies per COPC]
θ_{acap} = Air content of capillary fringe soils (in cm^3/cm^3)
θ_t = Total effective soil porosity (unitless)
D_w = Water diffusion coefficient (in cm^2/s) [varies per COPC]
θ_{wcap} = Water content of capillary fringe soils (in cm^3/cm^3)
H' = see equation above

$$D_{eff,s} = [D_a \times \frac{\theta_{as}^{10/3}}{\theta_t^2}] + [D_w \times \frac{\theta_{ws}^{10/3}}{H \times \theta_t^2}]$$

Where,

$D_{eff,s}$ = Effective diffusion coefficient in soil, based on vapour-phase concentration (in cm^2/s).
D_a = Gas diffusion coefficient (in cm^2/s) [varies per COPC]
θ_{as} = Vapour-filled porosity (unitless)
θ_t = Total effective soil porosity (unitless)
D_w = Water diffusion coefficient (in cm^2/s) [varies per COPC]
θ_{ws} = Moisture-filled porosity (unitless)
H' = see equation above

Table 3.5 presents the input parameters characterizing the soil, dimensions, and outdoor conditions. Table 3.6 presents chemical-specific input parameters (e.g. Henry's Law constants, etc.).

The results of groundwater trench-air vapour modelling, for on-site and off-site groundwater, are shown in Table 5.7 and Table 5.9.

Table 3.5 Trench-Air Groundwater Vapour Modelling: Soil and Outdoor Input Parameters

Input Parameter	Description	Units	Value	References & Comments
Soil Properties				
θ_t	total effective porosity	-	0.36	MOE (2011b) default for coarse is 0.36 and for fine 0.47
θ_{ws}	moisture-filled porosity	-	0.119	MOE (2011b) default is 0.119 for coarse and 0.168 for med/fine
θ_{as}	vapour-filled porosity	-	0.241	$= \theta_t - \theta_{ws}$
Outdoor				
U_{air}	wind speed above ground surface in a trench mixing zone	cm/s	100.0	Assumed; calmer conditions represent stagnant trench air.
δ_{air}	height of mixing cell	cm	200	MOE (2011b) default
W	Length of source zone	cm	1300	MOE (2011b) default
T	Temperature	°C °K	20 293	Assumed
R	Universal Gas Constant	atm·m^3/mol·K	8.314	-
h_{cap}	Thickness of capillary fringe	cm	5	ASTM (1995) default
h_v	Thickness of vadose zone	cm	5	Nominal value
L_{gw}	Depth to groundwater / water table	cm	100	Assumed trench is 1 m above groundwater level
θ_{acap}	Air content of capillary fringe soils	cm^3/cm^3	0.018	$= \theta_t - \theta_{wcap}$
θ_{wcap}	Water content of capillary fringe soils	cm^3/cm^3	0.342	ASTM (1995) default.

Table 3.6 Trench-Air Groundwater Vapour Modelling: COPC-Specific Input Parameters

COPC / Parameter	Description	Units	Value	References & Comments
Chloroethane				
D_a	Gas diffusion coefficient	cm^2/s	2.71E-01	-
D_w	Water diffusion coefficient	cm^2/s	1.15E-05	-
H	Henry's Law coefficient	$Pa•m^3/mol$	1.11E+03	-
K_{oc}	Organic carbon water partitioning coefficient	-	23.74	-
C_{gw}	Concentration in groundwater	mg/L	See Table 5.7 and Table 5.9	Max.; onsite 95th Percentile; onsite Max.; offsite 95th Percentile; offsite
1,1-Dichloroethene				
D_a	Gas diffusion coefficient	cm^2/s	9.00E-02	-
D_w	Water diffusion coefficient	cm^2/s	1.04E-05	-
H	Henry's Law coefficient	$Pa•m^3/mol$	2.61E+03	-
K_{oc}	Organic carbon water partitioning coefficient	-	35.04	-
C_{gw}	Concentration in groundwater	mg/L	See Table 5.7 and Table 5.9	Max.; onsite 95th Percentile; onsite Max.; offsite 95th Percentile; offsite
Cis-1,2-Dichloroethene				
D_a	Gas diffusion coefficient	cm^2/s	7.36E-02	-
D_w	Water diffusion coefficient	cm^2/s	1.13E-05	-
H	Henry's Law coefficient	$Pa•m^3/mol$	4.07E+02	-
K_{oc}	Organic carbon water partitioning coefficient	-	43.79	-
C_{gw}	Concentration in groundwater	mg/L	See Table 5.7 and Table 5.9	Max.; onsite 95th Percentile; onsite Max.; offsite 95th Percentile; offsite
trans-1,2-Dichloroethene				
D_a	Gas diffusion coefficient	cm^2/s	7.07E-02	-
D_w	Water diffusion coefficient	cm^2/s	1.19E-05	-
H	Henry's Law coefficient	$Pa•m^3/mol$	9.33E+02	-
K_{oc}	Organic carbon water partitioning coefficient	-	43.79	-
C_{gw}	Concentration in groundwater	mg/L	See Table 5.7 and Table 5.9	Max.; onsite 95th Percentile; onsite Max.; offsite 95th Percentile; offsite

COPC / Parameter	Description	Units	Value	References & Comments
Tetrachloroethene				
D_a	Gas diffusion coefficient	cm^2/s	7.20E-02	-
D_w	Water diffusion coefficient	cm^2/s	8.20E-06	-
H	Henry's Law coefficient	$Pa \cdot m^3/mol$	1.76E+03	-
K_{oc}	Organic carbon water partitioning coefficient	-	106.8	-
C_{gw}	Concentration in groundwater	mg/L	See Table 5.7 and Table 5.9	Max.; onsite 95th Percentile; onsite Max.; offsite 95th Percentile; offsite
1,1,1-Trichloroethane				
D_a	Gas diffusion coefficient	cm^2/s	7.80E-02	-
D_w	Water diffusion coefficient	cm^2/s	8.80E-06	-
H	Henry's Law coefficient	$Pa \cdot m^3/mol$	1.72E+03	-
K_{oc}	Organic carbon water partitioning coefficient	-	48.64	-
C_{gw}	Concentration in groundwater	mg/L	See Table 5.7 and Table 5.9	Max.; onsite 95th Percentile; onsite Max.; offsite 95th Percentile; offsite
Trichloroethene				
D_a	Gas diffusion coefficient	cm^2/s	7.90E-02	-
D_w	Water diffusion coefficient	cm^2/s	9.10E-06	-
H	Henry's Law coefficient	$Pa \cdot m^3/mol$	9.82E+02	-
K_{oc}	Organic carbon water partitioning coefficient	-	67.7	-
C_{gw}	Concentration in groundwater	mg/L	See Table 5.7 and Table 5.9	Max.; onsite 95th Percentile; onsite Max.; offsite 95th Percentile; offsite
Vinyl Chloride				
D_a	Gas diffusion coefficient	cm^2/s	1.06E-01	-
D_w	Water diffusion coefficient	cm^2/s	1.23E-06	-
H	Henry's Law coefficient	$Pa \cdot m^3/mol$	2.78E+03	-
K_{oc}	Organic carbon water partitioning coefficient	-	23.74	-
C_{gw}	Concentration in groundwater	mg/L	See Table 5.7 and Table 5.9	Max.; onsite 95th Percentile; onsite Max.; offsite 95th Percentile; offsite

3.3.2 Estimating Vapours from Soil: OMOE 2011

Overall, the OMOE 2011 (MOE 2011b) methodology calculates vapour concentrations as a function of the soil dimensions provided (e.g. length of mixing cell and height of source zone), the wind speed, and the vapour flux factor 'J' which incorporates the concentration of a chemical in soil.

Calculations are as follows:

$$C_{vap} = \frac{J \times Length}{Height \times Windspeed} \times CF$$

Where,

C_{vap}	=	Vapour concentration (µg/m^3)
Length	=	Length of the source zone (in cm)
Height	=	height of mixing cell (in cm)
U_{air}	=	Wind speed (in cm/s)
CF	=	Unit Conversion factor (cm to m; g to µg)
J	=	vapour flux leaving the ground surface (in g/cm^2•s) (see equation below)

$$J = Cs \times \sqrt{\frac{D_{eff}}{\pi \times t}} \times \left[1 - \exp\left(\frac{-d^2}{4 \times D_{eff} \times t}\right)\right]$$

Where,

J	=	vapour flux leaving the ground surface (in g/cm^2•s)
Cs	=	concentration in soil (in g/cm^3); chemical-dependent *[soil concentration in mg/kg, multiplied by soil bulk density, with unit conversion factor]*
t	=	time over which vapour migration occurs (assumed to be 1 year; i.e. 31,536,000 seconds)
d	=	depth to contamination (in cm)
D_{eff}	=	effective diffusion coefficient (in cm^2/s) (see equation below)

$$D_{eff} = \frac{\frac{n_a^{10/3} \times D_{air} \times H' + n_w^{10/3} \times D_w}{n^2}}{(\rho_b \times K_{oc} \times f_{oc} + n_w + n_a * H')}$$

Where,

D_{eff}	=	effective diffusion coefficient (in cm^2/s)
n_a	=	vapour-filled porosity (unitless)
n_w	=	water-filled porosity (unitless)
n	=	total porosity (unitless)
ρ_b	=	soil bulk density (g/cm^3)

K_{oc} = soil organic carbon water partitioning coefficient (unitless)
f_{oc} = fraction of organic carbon (%)
D_{air} = gaseous diffusion coefficient (cm^2/s) [chemical-dependent]
D_w = water (liquid) diffusion coefficient (cm^2/s) [chemical-dependent]
H' = see equation below

$$H' = \frac{H}{R \times T}$$

Where,

H = Henry's law coefficient (in $Pa \cdot m^3/mol$) [chemical-dependent]
R = universal gas constant (8.314 $atm \cdot m^3/mol \cdot K$)
T = Temperature (in °Kelvin)

Table 3.7 presents the input parameters characterizing the soil, dimensions, and outdoor conditions. Where there are parameters common to both groundwater-vapour and soil-vapour calculations, their values are consistent. For soil-vapour modelling, the same chemical-specific parameters are used as those for groundwater-vapour modelling, as shown in Table 3.6.

The results of soil trench-air vapour modelling are shown in Table 5.7 and Table 5.9.

Table 3.7 Trench-Air Soil Vapour Modelling: Soil and Outdoor Input Parameters

Input Parameter	Description	Units	Value	References & Comments
Soil Properties				
n	total effective porosity	-	0.36	MOE (2011b) default: coarse soil
n_w	moisture-filled porosity	-	0.119	MOE (2011b) default: coarse soil
n_a	vapour-filled porosity	-	0.241	= $\theta_t - \theta_{ws}$
ρ_b	soil bulk density	g/cm^3	1.7	MOE (2011b) default: coarse soil
f_{oc}	fraction of organic carbon	%	0.50	MOE (2011b) default: coarse soil
Outdoor				
U_{air}	wind speed above ground surface in a trench mixing zone	cm/s	100.0	Assumed; calmer conditions represent stagnant trench air.
Height	height of mixing cell	cm	200	MOE (2011b) default
Length	Length of source zone	cm	1300	MOE (2011b) default
T	temperature	°C °K	20 293	Assumed
R	Universal Gas Constant	$atm \cdot m^3/mol \cdot K$	8.314	-
T	Timespan	sec	31,536,000	Assumed to be 1 year.
D	Distance to contamination	cm	200	MOE (2011b) default

3.4 Surface Water Modelling: Municipal Sewage Outfall Discharge

The CFM Facility is located inland, and as such, has no direct liquid releases to surface water. Instead, the CFM Facility has monitored liquid releases (containing uranium) to the municipal sewer system which is subsequently piped to the municipal sewage treatment plant, combined with sewer releases from other sources serviced by the sewer system, and treated. The Port Hope Municipal Sewage Treatment Plant (STP) releases treated sewer effluent to Lake Ontario via an outfall diffuser located offshore.

Later risk assessment calculations assess the potential effects of uranium in CFM's liquid sewer effluent on humans and the environment. To do so, there is a need to estimate the concentration of uranium in surface water near the municipal outfall and also in surface water in the Port Hope harbour. These two estimates are performed separately, as described in the following subsections.

3.4.1 Estimating Surface Water Concentrations near the Municipal Outfall for EcoRA

The concentration of uranium in CFM liquid effluent is known – it is measured regularly as part of CFM's operational monitoring. CFM liquid effluent is released to the municipal sewer system, where it is combined with other sewer effluents at the STP; as a result, the concentration of uranium is diluted by the addition of these other liquid effluent volumes. Following this, sewage treatment processes (e.g. settling) would remove some portion of the uranium. Next, the treated effluent is released via the outfall diffuser, which is designed to rapidly disperse the treated effluent in surface water. Overall, in this sequence there are several factors that dilute, remove, and then disperse the uranium contained in CFM's liquid effluent contributions.

For the purposes of this assessment, the concentration of uranium in surface water near the municipal outfall diffuser is estimated in a very conservative manner: by deriving a dilution factor that accounts only for the dilution of uranium in CFM's liquid effluent into the total effluent volume of the STP. This is a very conservative approach because it does not take into account the removal of uranium by treatment processes, nor does it take into account the dispersion provided by the outfall diffuser design.

In 2014, the CFM Facility released 1.58 kg of Uranium as part of its 30,967 m^3 of effluent (Cameco 2015a; Table 29). This results in an overall (average) uranium concentration of 51.02 µg/L of CFM effluent. Table 3.8 presents the overall inflow (total sewer effluent received by the STP) and outflow (total effluent – post-treatment – released by the STP via the diffuser) of the STP (Cameco, 2015b). It is important to note that data for January to March and September to December shows inflows that are less than outflows; typical trends indicate the opposite, with inflows being greater than outflows (the difference being due to the volume and mass removed through treatment processes and disposed of via landfill). Reportedly this discrepancy is due to instrumentation issues experienced by the STP. Also, during the fall/winter months, sewage haulers increasingly unload sewage at the wastewater treatment plant rather than deferring to land use application (which is not effective during winter months). Overall, the instrumentation issues also affected data from summer months, but the effect is not as easily observed due to decreases in volumes of hauled wastewater received at the wastewater treatment plant during this time period. Nevertheless, the overall treated outflow data are believed to be sufficiently accurate for use in this assessment.

Table 3.8 2014 Port Hope Municipal STP Inflow and Outflow

Month	Raw Sewage Inflow (m^3)	Treated Outflow Release via Diffuser (m^3)
January	169,983	186,567
February	149,106	166,091
March	197,358	201,212
April	314,606	279,903
May	215,336	210,974
June	174,768	172,772
July	158,650	158,545
August	176,040	167,471
September	146,579	151,206
October	140,026	149,703
November	152,084	160,704
December	151,453	166,518
Total	2,145,989	2,171,666

Given the information above, the concentration of uranium from CMF effluent in the resulting STP effluent, is calculated using the following simple equation:

$$Concentration_1 \times Volume_1 = Concentration_2 \times Volume_2$$

Where:

C_1 = Concentration of uranium in CFM effluent (51.02 µg/L)
V_1 = Volume of CFM effluent (30,967 m^3)
C_2 = Concentration of uranium in total STP effluent (*to be estimated*)
V_2 = Volume of total STP effluent (2,171,666m^3)

Rearranging and solving the equation results in a concentration of uranium in overall STP effluent of 0.73 µg/L. This corresponds to a dilution factor of approximately 70x.

As discussed above, the dispersion offered by the diffuser is neglected (a conservative assumption), and the surface water near the diffuser is simply assumed to be equal to the effluent concentration (i.e. 0.73 µg/L).

3.4.2 Estimating Surface Water Concentrations at the Harbour

The Cornell Mixing Zone Expert System (CORMIX) (Doneker & Jirka, 2007) was used to perform dispersion calculations and develop a dilution factor that accounts for dispersion between the STP outfall and the harbour – the location where human receptors may become exposed to releases. The CORMIX model has been extensively verified by the developers through comparison of simulation results to available field and laboratory data on mixing processes, and has undergone independent peer review in journal proceedings.

To model an effluent plume using CORMIX, several input parameters are needed to characterize:

- The effluent,
- The outfall diffuser, and
- The ambient aquatic receiving environment.

These groups of input parameters are described in greater detail below. The reader is referred to the original Doneker & Jirka (2007) CORMIX model documentation for detailed descriptions of the modelling methodologies used.

Effluent Characteristics:

As mentioned above, CORMIX modelling was conducted using a unit-concentration of effluent (1 ppm), rather than specific concentrations of analytes in effluent. This allows for calculation of a generic dilution factor that can be applied to any particular analyte within effluent (regardless of its concentration). To maintain conservatism, dilution is modelled with no loss, decay, or degradation of the source effluent; in other words, all unit effluent released at the outfall is assumed to enter the receiving water body. Effluent characteristics are summarized in Table 3.9.

Table 3.9 CORMIX Modelling – Effluent Parameter Inputs

Parameter	Value/Selection	Notes
Effluent Concentration	1 ppm	Unit concentration used to derive generic dilution factor.
Effluent Loss	No loss/decay	No loss, decay, or degradation. (Conservative)
Effluent Flow Rate	245 m^3/h *(i.e. 2,145,989 m^3/yr)*	Cameco (2015b).
Effluent Temperature	20°C	Nominal value.

Outfall Diffuser Characteristics:

Outfall diffuser geometry and characteristics are based on the descriptions in Cameco (2015b) and its attachments (i.e., design drawings: PHSTP (2006) and PHSTP (1955)). The diffuser geometry (i.e. length, distance from shore, port height, port diameter, contraction ratio, number of ports, port/nozzle direction and orientation, and alignment angles [beta, sigma, gamma, and theta]) is summarized in Table 3.10.

Table 3.10 CORMIX Modelling – Outfall Diffuser Parameter Inputs

(Ref: Cameco 2015b, and attachments)

Parameter	Value/Selection	Notes
Release Type	Alternating Perpendicular	-
Nearest shore/bank	Left	-
Diffuser length	4 m	-
Distance to first port (from shore)	235 m	Outfall *centre* located at 237 m from shore.
Distance to last port (from shore)	239 m	
Port height (above bottom)	1 m	*
Port diameter	0.45 m	-
Contraction Ratio	1 (unitless)	CORMIX default value for well-rounded nozzle/opening.
Number of ports	3	*
Distance Between Ports	2 m	Assumed
Alignment Angle (Gamma)	90°	Angle between diffuser line and ambient current, measured counter-clockwise from ambient current direction.
Port/Nozzle configuration	Single	Each riser leads to a single port/nozzle. In other words, there are not multiple nozzles on each riser.
Port/Nozzle overall direction	Alternating Perpendicular	Nozzles do not point in the same direction.
Angle (Theta)	90°	Angle between the nozzle centreline and the horizontal plane.*
Angle (Sigma)	0°	Horizontal angle between the direction of discharge and the direction of ambient current flow, measured counter-clockwise from the ambient current direction.
Angle (Beta)	90° *(outlets facing 90° from pipe direction)*	Nearest angle between the horizontal projection of the average port/nozzle centreline direction, and the diffuser axis.
Nozzle Direction	*Same*	Nozzles not 'fanned out' along diffuser.

Note: * - Based on CORMIX outfall geometry data needs and parameter limits. A 1 m height above bottom was chosen, to accommodate CORMIX depth limit. In order to best approximate the T-shaped design of the STP outfall and preserve the multi-port outfall geometry in CORMIX, a 3-port diffuser configuration with a vertical component was defined as opposed to a single-port submerged T-design discharge.

Ambient Aquatic Receiving Environment Characteristics:

Table 3.11 presents the input parameters used to characterize the ambient aquatic receiving environment.

Table 3.11 Effluent Plume Modelling – Ambient Receiving Environment Parameter Inputs

(Ref: Cameco 2015b, and attachments, unless otherwise noted)

Parameter	Value/Selection	Notes
Average Depth (m)	4 m	Approximation based on location.
Depth at discharge (m)	3.1 m	-
Wind Speed (m/s)	5 m/s	Nominal, based on location.
Lake current type	Steady	-
Lake current velocity (cm/s)	0.04 cm/s	Nominal, based on location.
Bounded/Unbounded	Unbounded	-
Freshwater/Marine	Freshwater	-
Lake Temperature & distribution	*Uniform:* 15°C	Nominal, based on location.
Darcy-Weisbach Factor	0.061 (unitless)	Conservative nominal value, corresponding to very rough conditions.

CORMIX Results:

Given that the harbour is located approximately 2.1 km from the outfall diffuser (Cameco 2015b), a dilution of approximately 2090x is expected based on the modelling conditions. [redacted]

4.0 PRELIMINARY SCREENING - CONTAMINANTS OF POTENTIAL CONCERN

This section contains the preliminary screening process used to review measurement data from the different environmental media in order to identify Contaminants of Potential Concern (COPCs) that will require further evaluation in the risk assessment.

Overall, the screening process involves two steps:

1. **Preliminary screening** to identify an overall list of COPCs (documented in this section); and

2. **Secondary screening**, to determine which COPCs to include in the HHRA and which to include in the EcoRA. The HHRA secondary screening is documented in Section 5.1.2, and EcoRA secondary screening is documented in Section 6.1.3.

The preliminary screening step (documented in this section) is conducted by comparing maximum concentrations in environmental media to screening criteria from available standards (see Sections 4.2 to 4.7 for the hierarchies used). This step allows for the development of an initial list of COPCs; however, several screening criteria are based on the lowest concentration that is protective of human health *or* ecological species. Therefore, secondary screening steps are carried out later to further distinguish between COPCs requiring evaluation as part of the human health assessment, and those requiring evaluation as part of the ecological assessment.

In general, preliminary screening identifies COPCs (i.e. those analytes that are carried forward for further evaluation in the ERA) if the analyte satisfied one of the following 3 conditions:

1. The maximum concentration exceeds the corresponding screening criterion; or
2. a) there are measurable concentrations;

   b) corresponding screening criteria are not available; and

   c) toxicity benchmarks are available; or
3. They were identified in other relevant connected environmental media as COPCs (i.e., at levels exceeding screening criteria in those connected media) and are related to current site operations.

If an analyte is present in measurable concentrations, but screening criteria and toxicity data are not available, then the analyte is not considered for further assessment since the lack of toxicity data prevents meaningful assessment.

If an analyte does not have a corresponding screening criterion, but also has non-detect levels in media, then it is generally not considered for further evaluation. An exception to this rule exists if the analyte has been identified in a relevant connected media at measurable levels that exceed those criteria (due to the potential for the analyte to transfer between media). However, in such circumstances, a decision is made on a case-by-case basis based on the complexity of the site and the interaction of the different environmental media.

If an analyte *does* have a corresponding screening criterion, and has non-detect levels in media but at an MDL that is greater than the screening criterion, then it is generally included for further assessment; however, again in such circumstances a decision is made on a case-by-case basis based on the complexity of the site and the interaction of the different environmental media.

It is important to note however, that variations to the general procedure above may exist for select environmental media. Rationale for the screening decision for each analyte is provided in the screening tables.

Air:

Air screening follows the overall screening procedure outlined above using concentrations at the point of impingement (POI). The results of air screening are shown below in their respective sub-section.

Soil:

Soil screening follows the overall screening procedure outlined above, the results of soil screening are shown below in their respective sub-section.

Groundwater:

Groundwater screening follows the overall screening procedure outlined above. The results of groundwater screening are shown below in their respective sub-section. Those analytes that exceed their corresponding criteria are identified as COPCs and undergo further secondary screening for EcoRA (see Section 6.1.3). As groundwater is not used as a drinking source for humans, it does not undergo any further screening.

Surface Water:

Surface water screening follows the overall screening procedure outlined above; where maximum measured surface water concentrations are compared to their corresponding screening criteria. Analytes that exceed their corresponding criteria are identified as COPCs. Where additional rationale is incorporated and interpreted for screening, it is noted within the screening tables.

Sediment

Sediment screening follows the overall screening procedure outlined above; where maximum measured surface water concentrations are compared to their corresponding screening criteria. Analytes that exceed their corresponding criteria are identified as COPCs.

4.1 Gamma Measurements & Radionuclides – Preliminary Screening

For the purposes of this ERA, gamma measurement data is screened-in (i.e., are identified as stressors), and will undergo further risk evaluation for both HHRA and EcoRA. As natural uranium screened in, uranium isotopes and those in the decay chain are also screened in and will undergo further risk evaluation for both HHRA and EcoRA.

4.2 Groundwater - Preliminary Screening

Preliminary screening of groundwater data is presented in Table 4.1, where maximum measured concentrations from the CFM facility are compared to the lowest of the following groundwater screening criteria:

- MOE (2011a) *Soil, Groundwater and Sediment Standards* (Table 3b values); and
- Environment Canada (2015) *Federal Interim Groundwater Quality Guidelines.*

If no value was found in the above references, the following reference was also checked:

- Health Canada (2012) *Federal Drinking Water Quality Guidelines*

The MOE (2011a) Table 3b values (Non-Potable Ground Water Condition) were chosen. This is consistent with prior investigations at the facility.

Table 4.1 Groundwater: Preliminary Screening

Category	Parameter	Screening Criteria		Max. Groundwater Value	Evaluate as COPC?	Comments
		MOE (2011a)[1]	EC (2015)[2]			
		(mg/L)				
VOCs	Chloroethane (CA)	NA	NA	<5	**No**	<MDL and no screening criteria available
	1,1-Dichloroethylene (1,1-DCE)	0.017	0.49	0.0829	**Yes**	Exceeds lowest criteria
	cis-1,2-Dichloroethylene (cis-1,2-DCE)	0.017	0.03	0.804	**Yes**	Exceeds lowest criteria
	trans-1,2-Dichloroethylene (trans-1,2-DCE)	0.017	0.03	0.115	**Yes**	Exceeds lowest criteria
	Tetrachloroethylene (PCE)	0.017	0.11	0.114	**Yes**	Exceeds lowest criteria
	1,1,1-Trichloroethane (TCA)	6.7	1.1	0.119	**No**	
	Trichloroethylene (TCE)	0.017	0.029	226	**Yes**	Exceeds lowest criteria
	Vinyl Chloride (VC)	0.0017	0.013	0.147	**Yes**	Exceeds lowest criteria
Metals	Uranium	0.015	0.015	0.788	**Yes**	Exceeds lowest criteria

Notes:
[1] - MOE 2011a Table 3b Full Depth Generic Site Condition Standards in a Non-Potable Ground Water Condition (Medium and Fine Textured Soils)
[2] - Environment Canada (2015) Federal Interim Groundwater Quality Guidelines (Tier 1, Lowest Guideline value for *industrial* land use)
NA - Not Available

Based on the preliminary screening in Table 4.1, the following preliminary COPCs were identified:

1. 1,1-Dichloroethylene (1,1-DCE)
2. cis-1,2-Dichloroethylene (cis-1,2-DCE)
3. trans-1,2-Dichloroethylene (trans-1,2-DCE)
4. Tetrachloroethylene (PCE)
5. Trichloroethylene (TCE)
6. Vinyl Chloride (VC)
7. Uranium

4.3 Surface Water - Preliminary Screening

Preliminary screening of surface water data is presented in Table 4.2. Maximum measured concentrations (regardless of location) were compared to the following hierarchy of screening criteria:

- MOE (1999) *Provincial Water Quality Objectives (PWQOs); and,*
- CCME (2015a, online) *Water Quality Guidelines for the Protection of Aquatic Life; (*wherever MOE (1999) values were not available).

Based on the preliminary screening in Table 4.2, the following surface water COPCs were identified:

1. Trichloroethylene (TCE); and
2. Uranium.

Table 4.2 Surface Water: Preliminary Screening

Category	Parameter	Screening Criteria[1]	Max. Surface Water Value	Evaluate as COPC?	Comments
		(mg/L)			
VOCs	Chloroethane (CA)	NA	<0.001	**No**	<MDL and no screening criteria available
	1,1-Dichloroethylene (1,1-DCE)	0.04	0.0011	**No**	
	cis-1,2-Dichloroethylene (cis-1,2-DCE)	0.2	0.0043	**No**	
	trans-1,2-Dichloroethylene (trans-1,2-DCE)	0.2	<0.0005	**No**	
	Tetrachloroethylene (PCE)	0.05	<0.0005	**No**	
	1,1,1-Trichloroethane (TCA)	0.07	0.0029	**No**	
	Trichloroethylene (TCE)	0.02	0.103	**Yes**	Exceeds screening criteria
	Vinyl Chloride (VC)	0.6	<0.0005	**No**	
Metals	Uranium	0.005	0.0895	**Yes**	Exceeds screening criteria

[1] - MOE Provincial Water Quality Objectives (1994; 1999) [PIBS 3303E]

NA - Not available

4.4 Air - Preliminary Screening

The preliminary air quality screening is presented in Table 4.3, showing:

- point of impingement concentrations in air, based on results in 2015 Emissions Summary Dispersion Model (ESDM) report for CFM (Cameco 2016);
- air quality screening criteria obtained from *Ontario Regulation 419/05 – Air Pollution – Local Air Quality* as of July 1, 2016; and
- the overall decision as to whether or not to identify each compound as a COPC requiring further evaluation in the risk assessment.

As shown in Table 4.3, no contaminant exceeded screening criteria in air.

Table 4.3 Air: Preliminary Screening

Contaminant	Averaging Period	Screening Criteria ($\mu g/m^3$)[a]	POI Concentration ($\mu g/m^3$)	Evaluate as COPC?	Comments:
1,1-Dichloroethylene (1,1-DCE)	0.5 hr	30	0.537	No	
1,2,3-benzotriazole	0.5 hr	120 [c]	0.661	No	
Aluminum Oxide	0.5 hr	100 [b]	0.0694	No	
Aminomethoxyethanol	0.5 hr	456 [c]	11	No	
Chromium	0.5 hr	1.5	0.0000444	No	
cis-1,2-Dichloroethylene (cis-1,2-DCE)	0.5 hr	315 [b]	1.52	No	
Copper	0.5 hr	100	0.00000444	No	
Dibenzoyl Peroxide	0.5 hr	36 [c]	0.0177	No	
Distillates, petroleum, hydrotreated heavy naphthenic	0.5 hr	48 [c]	11	No	
Hafnium	0.5 hr	3.6 [c]	0.000444	No	
Iron	0.5 hr	10	0.0000444	No	
Methyl Methacrylate	0.5 hr	860	2.17	No	
Molybdenum	0.5 hr	100 [b]	0.0000888	No	
Nickel	0.5 hr	0.6	0.00000444	No	
Nitrogen oxides	0.5 hr	500	36.3	No	
Suspended Particulate	0.5 hr	100	0.158	No	
Tetrachloroethylene (PCE)	0.5 hr	1080	1.03	No	
Tin	0.5 hr	30	0.000133	No	
trans-1,2-Dichloroethylene (trans-1,2-DCE)	0.5 hr	315 [b]	0.896	No	
Trichloroethylene (TCE)	0.5 hr	36	8.67	No	
Uranium and compounds	0.5 hr	0.45	0.0646	No	
Vinyl Chloride (VC)	0.5 hr	3	0.448	No	
Zinc	0.5 hr	100	0.00125	No	
Zirconium	0.5 hr	5 [d]	0.00437	No	

[a] - Ontario Regulation 419/05 as of July 1, 2016 , Schedule 2; unless otherwise indicated

[b] – Half-hour POI limit (MOE 2001)

[c] – Jurisdictional screening level (JSL) (MOE 2008)

[d] – Cameco Proposed Maximum Concentration Level Assessment for MOE Air CofA #7385-5QCSL5 submitted May 25, 2006 (Cameco 2016)

4.5 Soil - Preliminary Screening

Preliminary screening of soil data is presented in Table 4.4. Maximum measured concentrations (regardless of location) were compared to the lowest of the following soil screening criteria:

- MOE (2011a) Table 3b - *Full Depth Generic Site Condition Standards in a Non-Potable Ground Water Condition (Industrial Land-Use) Medium and Fine Textured Soils*; and
- CCME (2015b; online) *Soil Quality Guidelines for the Protection of Environmental and Human Health*.

Similar to the discussion for groundwater (see Section 4.2), soil criteria from MOE (2011a) Table 3b (non-potable water condition) where chosen. This is consistent with prior site investigations.

Based on the preliminary screening in Table 4.4, no contaminants exceeded screening criteria in soil.

Table 4.4 Soil: Preliminary Screening

Parameter	Screening Criteria (mg/kg)		Max. Soil Concentration (mg/kg)	Evaluate as COPC?	Comments:
	MOE (2011a) Table 3b Standard[1]	Applicable CCME Standard[2]			
Uranium	33	23	17.4	No	
Acetone (2-Propanone)	28		<0.1	No	
Benzene	0.4	Coarse: 0.03 Fine: 0.0068	0.004	No	
Bromodichloromethane	18		<0.002	No	
Bromoform	1.7		<0.002	No	
Bromomethane	0.05		<0.003	No	
Carbon Tetrachloride	1.5	50	<0.002	No	
Chlorobenzene	2.7		<0.002	No	
Chloroform	0.18	50	<0.002	No	
Dibromochloromethane	13		<0.002	No	
1,2-Dichlorobenzene	8.5	10	<0.002	No	
1,3-Dichlorobenzene	12	10	<0.002	No	
1,4-Dichlorobenzene	0.84	10	<0.002	No	
1,1-Dichloroethane	21	50	<0.002	No	
1,2-Dichloroethane	0.05	50	<0.002	No	
1,1-Dichloroethylene (1,1-DCE)	0.48	50	<0.002	No	
cis-1,2-Dichloroethylene (cis-1,2-DCE)	37		<0.002	No	
trans-1,2-Dichloroethylene (trans-1,2-DCE)	9.3		<0.002	No	
1,2-Dichloropropane	0.68	50	<0.002	No	
cis-1,2-Dichloropropene		50	<0.002	No	
trans-1,2-Dichloropropene		50	<0.002	No	
1,3-Dichloropropene	0.21		<0.002	No	
Ethylbenzene	19	Coarse: 0.082 Fine: 0.018	<0.002	No	
Ethylene Dibromide	0.05		<0.002	No	
Methylene Chloride (Dichloromethane)		50	<0.003	No	

Parameter	Screening Criteria (mg/kg)		Max. Soil Concentration (mg/kg)	Evaluate as COPC?	Comments:
	MOE (2011a) Table 3b Standard[1]	Applicable CCME Standard[2]			
Methyl Isobutyl Ketone	210		<0.03	No	
Methyl Ethyl Ketone (2-Butanone)	88		<0.03	No	
Methyl t-butyl ether (MTBE)	3.2		<0.002	No	
Styrene	43	50	<0.002	No	
1,1,1,2-Tetrachloroethane	0.11		<0.002	No	
1,1,2,2-Tetrachloroethane	0.094	0.6	<0.002	No	
Tetrachloroethylene (PCE)	21	0.6	<0.002	No	
Toluene	78	Coarse: 0.37 Fine: 0.08	0.015	No	
1,1,1-Trichloroethane (TCA)	12	50	<0.002	No	
1,1,2-Trichloroethane	0.11	50	<0.002	No	
Trichloroethylene (TCE)	0.61	0.01	0.003	No	
Vinyl Chloride (VC)	0.25		<0.002	No	
p+m-Xylene	NA		0.017	No	
o-Xylene	NA		0.004	No	
Xylene (Total)	30	Coarse: 11 Fine: 2.4	0.021	No	
Chloroethane (CA)	NA		ND	No	

Notes:

[1] MOE (2011a) Table 3b - Full Depth Generic Site Condition Standards in a Non-Potable Ground Water Condition

[2] CCME (2015b) online Soil Quality Guidelines

4.6 Sediment - Preliminary Screening

Preliminary screening of sediment data is presented in Table 4.5. Maximum measured concentrations (regardless of location) in 2014 from the CFM ongoing environmental monitoring program (SNC 2015a) were compared to the following screening criteria:

- Thompson, P.A., Kurias, J. and Mihok, S. (2005) *Derivation and use of sediment quality guidelines for ecological risk assessment of metals and radionuclides released to the environment from uranium mining and milling activities in Canada.*

Table 4.5 Sediment: Preliminary Screening

Category	Parameter	Screening Criteria[1]	Max. Sediment Concentration	Evaluate as COPC?	Comments
		(mg/kg)			
Metals	Uranium	104.4	4	No	

[1] - Thompson, P.A., Kurias, J. and Mihok, S. (2005) *Derivation and use of sediment quality guidelines for ecological risk assessment of metals and radionuclides released to the environment from uranium mining and milling activities in Canada*

NA - Not available

Only uranium measurements were available and the maximum concentration did not exceed screening criteria.

4.7 Summary - Preliminary Screening

The individual COPC lists generated by preliminary screening of each environmental medium are combined and presented in Table 4.6 below. If a contaminant screened out in all media, it is not included in the table below. Uranium and trichloroethylene are directly relevant to site operations and they were identified as COPC in groundwater and surface water. Therefore, even though chloroethane and 1,1,1-trichloroethane were not identified as COPC in all the media assessed, they are screened in as degradation by-products of TCE. As a result, uranium, trichloroethylene and its degradation by-products are carried through for further consideration in the HHRA and EcoRA.

It is important to note that uranium isotopes are considered COPCs, and will undergo further evaluation despite the lack of direct uranium isotope measurements – see Section 5.2.2.2 for more information on radionuclide inferences.

Table 4.6 Summary of Preliminary Screening COPCs

Category	Parameter	Soil	Groundwater	Surface Water	Sediment	Air (Stack)
VOCs	Chloroethane (CA)	N	N	N	ND	ND
	1,1-Dichloroethylene (1,1-DCE)	N	**Y**	N	ND	N
	cis-1,2-Dichloroethylene (cis-1,2-DCE)	N	**Y**	N	ND	N
	trans-1,2-Dichloroethylene (trans-1,2-DCE)	N	**Y**	N	ND	N
	Tetrachloroethylene (PCE)	N	**Y**	N	ND	N
	1,1,1-Trichloroethane (TCA)	N	N	N	ND	ND
	Trichloroethylene (TCE)	N	**Y**	**Y**	ND	N
	Vinyl Chloride (VC)	N	**Y**	N	ND	N
Metals	U	N	**Y**	**Y**	N	N
Rad	Uranium isotopes and decay chain	Y (all radionuclides included as COPCs)				

4.8 Uncertainties in Preliminary COPC Screening

- The screening methodology has been set up to minimize uncertainty: in the absence of screening criteria, contaminants are 'screened-in', i.e., retained as COPCs.
- The main uncertainties in the preliminary screening process are likely to be gaps in the data and gaps in the available screening criteria. As discussed earlier, large gaps were not identified in the ERA data set. With respect to screening criteria, in the absence of MOE screening values, other values such as background levels were used for screening. *Degree of uncertainty: Low.*
- Secondary screening, based on human health and ecological component values, is conducted and discussed in later sections of this report.

5.0 HUMAN HEALTH RISK ASSESSMENT

A HHRA is the evaluation of the probability of health consequences to humans caused by the presence of chemical contaminants at a Site. To assess this probability it is necessary to take receptor characteristics, exposure pathways and mitigating circumstances into consideration. The assessment of levels of unacceptable risk is evaluated using: toxicological information associated with the particular contaminants of concern; chemical and physical Site conditions; and known characteristics of the people interacting with the Site or connected media.

The requirement for, approach to, and scope of, a HHRA is based on a fundamental understanding of: site conditions, including the nature, extent and distribution of the radiological and chemical hazards; the potential exposure pathways; and opportunities for human receptors that will frequent, use or populate the Site. The following sections describe the HHRA and its components.

5.1 Problem Formulation

5.1.1 Receptor Selection & Characterization

It is important to note that under CSA N288.6 (2012), HHRAs apply to off-site receptors (i.e., members of the public) and on-site non-nuclear energy workers (non-NEWs) that are not covered under the facility's radiation protection program or health and safety program. At the CFM facility, all Cameco workers that perform industrial work are NEWs. Non-NEW contractors, such as maintenance workers, may be present up to a maximum of 80 hours per year.

As such, a total of eight human receptor groups have been identified for inclusion in the HHRA; one of these is an on-site Cameco industrial worker (characterized as a receptor but excluded from quantitative evaluation, as discussed above), two of these are onsite contractor workers (adults), three of these are offsite worker receptors (e.g. utilities workers) (adults), one is a member of the public (including all age groups) that resides within the study area, and one is an onsite contractor worker who also is a resident within the study area (adult only).

Table 5.1 presents the complete list of human receptors along with their descriptions.

Table 5.1 HHRA: Identification of Human Receptors

No.	Type of Receptor		Description	Age Variants
0	On-Site	Industrial On-Site Workers (NEW)	Industrial Workers perform facility operations and are assumed to work inside only. Potential exposure would come from: - air inhalation and immersion - groundwater vapour inhalation - soil vapour inhalation - gamma (radiological only) ***NOTE**: As outlined in CSA (2012) N288.6 NEWs are beyond the scope of N288.6 and are not assessed using HHRA methodology; health and safety of such workers is upheld by way of the facility's occupational radiation safety program and conventional health and safety programs. As such, no further investigation is require in this N288.6 ERA.*	Adult
1	On-Site	Maintenance On-Site Worker	On-Site Maintenance Workers are contractors that perform maintenance-type activities (e.g. landscape work, or repairs/inspections of equipment. They are present for short periods of time (not exceeding 2 weeks; with little time spent in any one particular area: i.e. <40 hours), and are assumed to potentially conduct work inside or outside. The key exposure represented by this receptor is inhalation of onsite indoor air, including vapours. Potential exposure would come from: - air inhalation and immersion - onsite soil ingestion, inhalation (dust) and dermal contact - vapour inhalation - gamma (radiological only) - external dose from soil deposits (by area) [radiological only]	Adult
2	On-Site	Sub-surface On-Site Worker	On-site Sub-surface Workers are contractors that perform sub-surface activities such as installation, inspection, or repairs to underground utilities; or soil/groundwater sample collection; or operation of the groundwater treatment system. They are present for short periods of time (not exceeding 2 weeks), and are assumed to potentially conduct work inside or outside. The key exposure represented by this receptor is direct access to *onsite* groundwater, via digging trenches deep enough to contact groundwater and accumulate vapours that are subsequently inhaled. Potential exposure would come from: - air inhalation and immersion - onsite soil ingestion, inhalation (dust) and dermal contact - onsite groundwater ingestion and dermal contact - onsite soil vapour inhalation (trench) - onsite groundwater vapour inhalation (trench)	Adult

No.	Type of Receptor		Description	Age Variants
			- gamma (radiological only) - external dose from soil deposits (by area) [radiological only]	
3	Off-Site	Commercial Off-Site Worker	Off-site Commercial workers are members of the public who work full-time in nearby offsite buildings. They are assumed to work indoors for the duration of their occupational exposure time. Potential exposure would come from: - air inhalation and immersion - offsite soil vapour inhalation - offsite groundwater vapour inhalation - gamma (radiological only)	Adult
4	Off-Site	Maintenance Off-site Worker	Off-site Maintenance workers are members of the public who work full-time at nearby offsite facilities performing outdoor work such as lawn care, maintenance, etc. They are assumed to work outdoors for the duration of their occupational exposure time. Potential exposure would come from: - air inhalation and immersion - offsite soil ingestion, inhalation (dust) and dermal contact - gamma (radiological only) - external dose from soil deposits (by area) [radiological only]	Adult
5	Off-Site	Sub-surface Off-Site Worker	Offsite Sub-surface Workers are members of the public who perform short-term sub-surface work outdoors, near the CFM facility (i.e. hydro workers). They are assumed to work outdoors only, and to be present in an offsite location near CFM for up to 1 week per year. The key exposure represented by this receptor is direct access to *offsite* groundwater, via digging trenches deep enough to contact groundwater and accumulate vapours which are subsequently inhaled. Potential exposure would come from: - air inhalation and immersion - offsite soil ingestion, inhalation (dust) and dermal contact - offsite groundwater ingestion and dermal contact - offsite groundwater vapour inhalation (trench) - offsite soil vapour inhalation (trench) - gamma (radiological only) - external dose from soil deposits (by area) [radiological only]	Adult
6	Off-Site	Resident	Off-site Residents are members of the public that habitat in the residential areas west and north of the CFM facility. They are assumed to spend time indoors and also outdoors. They engage in gardening activities, and their backyard produce comprises a portion of their diet. They also engage in fishing activities at the Port Hope harbour, and their caught fish comprises a portion of their	**Rad*:** -Infant -Child

No.	Type of Receptor		Description	Age Variants
			diet. These residences are supplied with municipal drinking water, and therefore it is assumed that groundwater or surface water are not used as drinking water. Potential exposure would come from: - air inhalation and immersion - offsite soil ingestion, inhalation (dust) and dermal contact - ingestion of backyard produce - ingestion of fish - gamma (radiological only) - external dose from soil deposits (by area) [radiological only]	-Adult **Non-Rad*:** -Infant -Toddler -Child -Teen -Adult
7	Off-Site	Resident & On-Site Sub-Surface Worker	The Off-site Resident & Worker receptor encompasses the exposures of both the 'Resident Receptor' (#6 above) as well as the 'On-Site Sub-Surface Worker Receptor' (#2 above). This receptor is assumed to be a resident that also works as the onsite subsurface worker. Potential exposure would come from: - air inhalation and immersion - Onsite soil ingestion, inhalation (dust) and dermal contact - Onsite soil vapour inhalation (trench) - Onsite groundwater ingestion and dermal contact - Onsite groundwater vapour inhalation (trench) - Offsite soil ingestion, inhalation (dust) and dermal contact - ingestion of backyard produce - ingestion of fish - gamma (radiological only) - external dose from soil deposits (by area) [radiological only]	Adult

** Age groups recommended for radiological assessment as per CSA N288.1 (2014). Age groups recommended for non-radiological assessment as per CSA N288.6 (2012).

5.1.2 Human Health Secondary Screening of COPCs

5.1.2.1 Groundwater - Human Health Secondary Screening

Groundwater data focus on uranium, trichloroethylene and its degradation products. These contaminants in groundwater do not require secondary human health screening, as they have been included as COPCs due to their relevance to site operations and the fact that they have been identified as COPCs in other relevant connected media.

5.1.2.2 Soil - Human Health Secondary Screening

Soil data focus on uranium, trichloroethylene and its degradation products. These contaminants in soil do not require secondary human health screening, as they have been included as COPCs due to their relevance to site operations and the fact that they have been identified as COPCs in other relevant connected media.

5.1.3 HHRA Exposure Pathways

The next step is to examine the potential pathways of exposure and identify the ways in which human receptors could be exposed to COPCs and radiological stressors present in the different environmental media, as identified in Sections 4.7 (preliminary COPC identification) and 5.1.2 (secondary HHRA COPC identification).

In general, human receptors may come into contact with contaminants through four primary exposure routes: dermal exposure, incidental ingestion (of for example, soil), ingestion of contaminated food, and inhalation. Therefore, a complete exposure pathway consists of a contaminant source, a release mechanism, one or more transport mechanisms, a point of exposure (receptor), and an exposure route for intake into the human body.

For gamma and other external radiation, exposure can occur externally without one of the four primary exposure routes. As a result, external radiation dose rates are included in this HHRA.

5.1.3.1 Soil Exposure Pathways

Based on the types of receptors, their characteristics, and their behaviours as described in Section 5.1.1, select human receptors may come into ***direct*** contact with soil, resulting in the following potential soil exposures:

- Dermal exposure to soil;
- Incidental ingestion of soil; and,
- Inhalation of airborne particulates (dust) that contains contaminated soil.

Indirect exposure to volatile soil contaminants can also occur via inhalation of soil vapours, as discussed below:

- Inhalation of soil vapours that have migrated indoors;

- Inhalation of soil vapours that have accumulated in subsurface areas (trenches); and,
- Inhalation of outdoor soil vapours that have migrated up through the soil (not assessed; see Section 5.1.3.6 for discussion).

Exposure to soil vapour varies for each receptor though only the Sub-Surface Worker receptors receive exposure to soil-trench-vapours, as shown in Table 5.2.

5.1.3.2 Groundwater Exposure Pathways

Based on the type of receptors, their characteristics, and their behaviours as described in Section 5.1.1, only Sub-Surface Worker receptors may come into ***direct*** contact with contaminated groundwater, resulting in the following groundwater exposures:

- Dermal exposure to groundwater; and
- Incidental ingestion of groundwater.

Indirect exposure to volatile groundwater contaminants can also occur via inhalation of groundwater vapours, as discussed below:

- Inhalation of groundwater vapours that have migrated indoors;
- Inhalation of groundwater vapours that have accumulated in subsurface areas (trenches); and,
- Inhalation of outdoor groundwater vapours that have migrated up through the soil (not assessed; see Section 5.1.3.6 for discussion).

Exposure to groundwater vapour varies for each receptor though only the Sub-Surface Worker receptors receive exposure to groundwater-trench-vapours, as shown in Table 5.2.

5.1.3.3 Air Exposure Pathways

Though air screening did not identify any COPCs that exceed their corresponding air concentration criteria, uranium has been included for air inhalation assessment due to its relevance to site operations, and because it has been identified as a COPC in other relevant connected media.

Human receptors can be exposed to indoor air, or outdoor air, or a combination of both. It is important to note that indoor and outdoor air are considered to be distinct from *vapours* (from soil or groundwater) and from *trench vapour* (also from soil or groundwater); and as such, exposures to these media are typically assessed separately. However, an exception exists where *measured* indoor air concentration data are available because such measured data implicitly includes all contributions from vapours and other sources. As a result, wherever measured indoor air data are available they are used preferentially, and, specific vapour-pathway exposures are not calculated as this exposure is encompassed by the measurement data used. A detailed breakdown of all exposure pathways for each receptor is presented in Table 5.2.

5.1.3.4 Contaminated Food Exposure Pathways

Based on their characteristics and behaviour as described in Section 5.1.1, off-site receptors (members of the public), may come into contact with contaminated foods resulting in exposure to air, soil and water contaminants. This includes:

- Consumption of fish caught locally (and resulting ingestion of surface water COPCs taken up by the fish); and
- Consumption of garden produce grown in off-site soil (and resulting ingestion of off-site soil COPCs taken up by the vegetation and deposition of air COPCs to vegetation).

As described in Section 5.1.1, locally obtained fish and garden produce, comprise only a portion of the total dietary intake of the receptor. The proportions of locally obtained foods used in this study are outlined in Table 5.5.

It is important to note that a key conservative assumption is that ingested fish are assumed to be caught from the Port Hope harbor area, where exposure to liquid effluent from the CFM facility occurs, after the combined sewage effluent has been discharged and mixed with the surrounding surface water accounting for distance from the outfall.

Detailed breakdowns of the food ingestion exposure pathway, distinguishing between the different human receptors, are presented in Table 5.2.

5.1.3.5 Gamma Radiation Exposure Pathway

Based on the characteristics and behaviour as described in Section 5.1.1, human receptors that are present in or near the CFM facility may experience external gamma exposure.

Gamma radiation doses are assessed based on direct external gamma radiation exposure. The dose rate from gamma radiation is added to the dose rate estimated from radionuclides in environmental media.

5.1.3.6 Summary of Inactive/Non-Applicable Exposure Pathways

Based on the receptor descriptions and the defined activities they engage in, the following exposure pathways are not applicable:

- *External Exposure from Immersion in air (Radiological)*

In many cases immersion in air is not a dominant contributor to overall radiological dose. The external dose contributed by air immersion is typically low enough to be neglected; only when specific conditions exist - such as confined spaces (where radionuclide levels can accumulate) or elevated concentrations of radionuclides in air – does the dose contribution from air immersion increase and warrant consideration. Furthermore, air COPC screening shows that air concentrations are below their corresponding criteria. Therefore, external radiological dose from air immersion can be excluded from further assessment.

- *Inhalation of Outdoor Vapours from Soil or Groundwater*

Inhalation of outdoor vapours from soil or groundwater are not a relevant pathway for all but Sub-surface Worker receptor. The Resident receptor, Maintenance Worker receptors (onsite and offsite), and Sub-Surface Worker receptor (onsite and offsite) engage in outdoor activities which could exposure them to outdoor vapours; however, the Resident receptor and Maintenance Worker receptor (onsite and offsite) are not located in areas where such outdoor vapours could accumulate and it is therefore reasonable to assume that outdoor vapours would disperse quickly resulting in little exposure (for these particular receptors). The Sub-Surface

Receptor however, *is* potentially located in an area where vapours have the potential to accumulate (i.e. in a trench), and the resulting exposure to groundwater-trench-vapour and soil-trench-vapour *is* assessed (though separately, since trench-air is considered to be distinct from outdoor air/vapour or indoor air/vapour).

- *Inhalation of Indoor Vapours from Offsite Soil*

The resident, off-site maintenance worker, and offsite sub-surface worker receptors engage in activities that cause them to experience soil exposure; however, inhalation of vapours from offsite soil is not a relevant pathway because volatile soil COPCs (TCE and its related compounds; for which vapour pathways can be assessed) are relevant to on-site soil contamination only. Though VOC measurement data are not available for offsite soil, there is no reason to believe that offsite soil VOC contamination exists as a result of CFM operations. It is important to note that this applies to offsite soil only; onsite soil is assessed for vapour inhalation.

- *Direct Surface Water Exposure Pathways*

The CFM facility discharges liquid effluent to the municipal sewage system, not directly to the lake. The combined municipal sewer discharge undergoes treatment before being ultimately released into the lake, via the offshore sewage release outfall. As such, in terms of surface water contaminants related to the CFM facility, direct uptake of surface water through use as drinking water, swimming, or beach recreation near the municipal sewage outfall are not considered to be reasonable exposure pathways, based on the site characteristics, location and surrounding area.

However, as outlined in Section 5.1.3.4, exposure to surface water contaminants via fish ingestion is possible as a portion of a fish's home range could overlap with the location of the sewage outfall.

- *Sediment Exposure Pathways*

Exposure from dermal contact can occur from direct contact with bulk sediments as well as with suspended sediments in the water column. As swimming in surface water is not considered as an exposure pathway, inhalation of or dermal contact with sediment was not considered.

- *Ingestion of Wild Game*

The facility is located in an urban area and no hunting takes place with the study area; therefore, ingestion of wild fowl and game was not considered.

5.1.3.7 Summary of Active HHRA Exposure Pathways

An overall summary of human receptor exposure pathways is presented in Table 5.2. More detailed descriptions related to the each environment medium (soil, groundwater, and surface water) are described in their respective sections above. Table 5.4 outlines the various environmental media and the pathways that link them to the human receptors.

Table 5.2 HHRA Exposure Pathways

PATHWAYS	On-Site Industrial Worker No. 0	On-Site Maintenance Worker No. 1	On-Site Sub-Surface Worker No.2	Off-Site Commercial Worker No. 3	Off-Site Maintenance Worker No. 4	Off-Site Subsurface Worker No. 5	Resident No. 6	Resident & Worker No. 7
Dermal contact with soil	N	Y	Y	N *(Direct soil and GW activities not part of receptor behaviour)*	Y	Y	Y	Y
Dermal contact with groundwater	N	N *(No access to GW; addressed via Subsurface. Receptor)*	Y		N *(No access to GW; addressed via Subsurface Receptor)*	Y	N *(No access to GW; addressed via Subsurface Receptor)*	Y
Dust inhalation	N	Y	Y		Y	Y	Y	Y
Incidental ingestion of soil	N	Y	Y		Y	Y	Y	Y
Incidental ingestion of groundwater	N	N *(No access to GW; addressed via Subsurface Receptor)*	Y		N *(No access to GW; addressed via Subsurface Receptor)*	Y	N *(No access to GW; addressed via Subsurface Receptor)*	Y
Inhalation of outdoor air	N	N *(Addressed via Subsurface. Receptor)*	Y	N *(Receptor located indoors)*	Y	Y	Y	
Inhalation of indoor air	Y	Y	N *(Addressed via Maint. Receptor)*	Y *(Assessed using measured indoor air levels)*	N *(Receptor is located outdoors)*	N *(Receptor is located outdoors)*	Y (Conservatively assessed using outdoor air; since residential indoor air is normally assumed to be 50% of outdoor air)	
Inhalation of vapours from soil (to outdoor air)	Y	N *(Not located in an outdoor area where vapours can accumulate - see Section 5.1.3.3)*	Y *(Assessed for trench soil-vapours)*	N *(Receptor located indoors)*	N *(Not located in an outdoor area where vapours can accumulate - see Section 5.1.3.3)*	N (No volatile COPCs in offsite soil see Section 5.1.3.6)	N *(Not located in an outdoor area where vapours can accumulate - see Section 5.1.3.3; no volatile COPCs in offsite soil, see Section 5.1.3.6)*	**Onsite Soil: Y** (Assessed for onsite soil-trench-vapours) **Offsite Soil: N** (No volatile COPCs in offsite soil see Section 5.1.3.6)
Inhalation of vapours from soil (to indoor air)	Y	Y *(implicitly included in indoor air inhalation exposure, by using measured indoor air data)*		**Offsite Soil: N** (No volatile COPCs in offsite soil see Section 5.1.3.6)	N *(Receptor is located outdoors)*	N *(Receptor is located outdoors)*	**Offsite Soil: N** (No volatile COPCs in offsite soil see Section 5.1.3.6)	**Onsite Soil: Y** (Assessed for onsite soil-trench-vapours)
Inhalation of vapour from groundwater (to outdoor air)	Y	N *(No access to GW; addressed via Subsurface. Receptor)*	Y *(Assessed for trench GW-vapours)*	N *(Receptor located indoors)*	N *(Not located in an outdoor area where vapours can accumulate - see Section 5.1.3.3)*	Y *(Assessed for trench GW-vapours)*	N *(Not located in an outdoor area where vapours can accumulate - see Section 5.1.3.3)*	Y *(Assessed for trench GW-vapours)*
Inhalation of vapour from groundwater (to indoor air)	Y			Y *(Vapour contribution is implicitly included via use of total measured indoor air concentrations)*	N *(Receptor is located outdoors)*	N *(Receptor is located outdoors)*	N *(Residences located upgradient from CFM facility; no GW-vapour pathways to CFM-related COPCs)*	
Drinking water intake	N *(Municipal Water Used as Drinking Water)*							
Ingestion of local fish	N *(Addressed via Resident & Resident-Worker Receptors)*						Y	Y
Ingestion of local backyard produce	N *(Addressed via Resident & Resident-Worker Receptors)*						Y	Y
External exposure from soil deposits (radiological only)	Y	Y	Y	N *(Receptor located indoors)*	Y	Y	Y	Y
Direct gamma (radiological only – external dose pathway)	Y	Y	Y	Y	Y	Y	Y	Y

5.1.4 HHRA Conceptual Site Model (CSM)

The overall HHRA study boundaries are based on knowledge of the site and surrounding area, and includes a range of known and potential contamination sources. Figure 5.1 presents the location of human receptors.

Figure 5.2 outlines the many environmental media included in this study, along with the exposure pathways that link these environmental media to human receptors.

Figure 5.3 and Figure 5.4 together present a graphical conceptual site model, based on the known COPCs and their locations, identified receptors, and relevant exposure pathways.

Figure 5.1 Human Receptor Locations

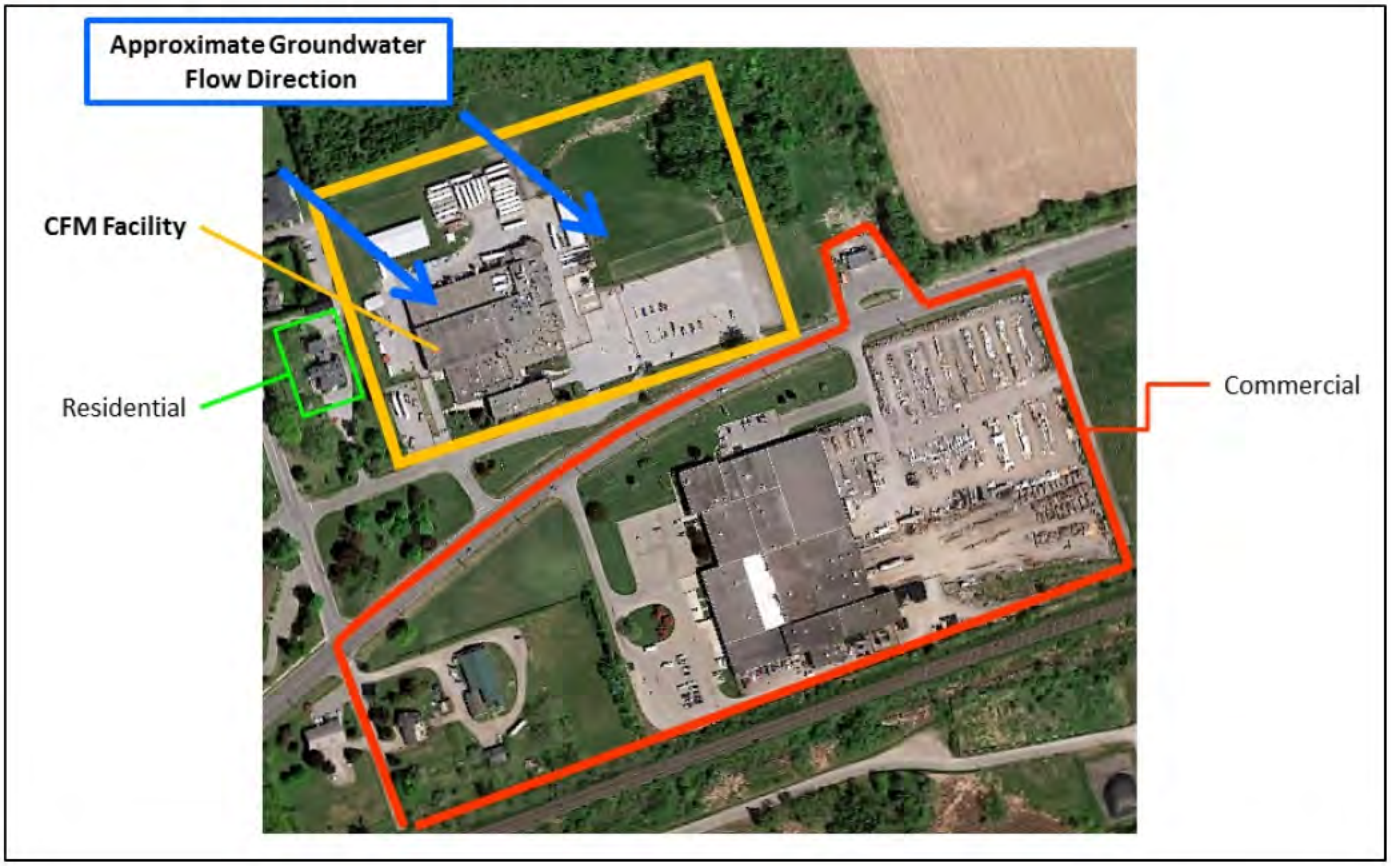


Figure 5.2 Human Receptor Pathways

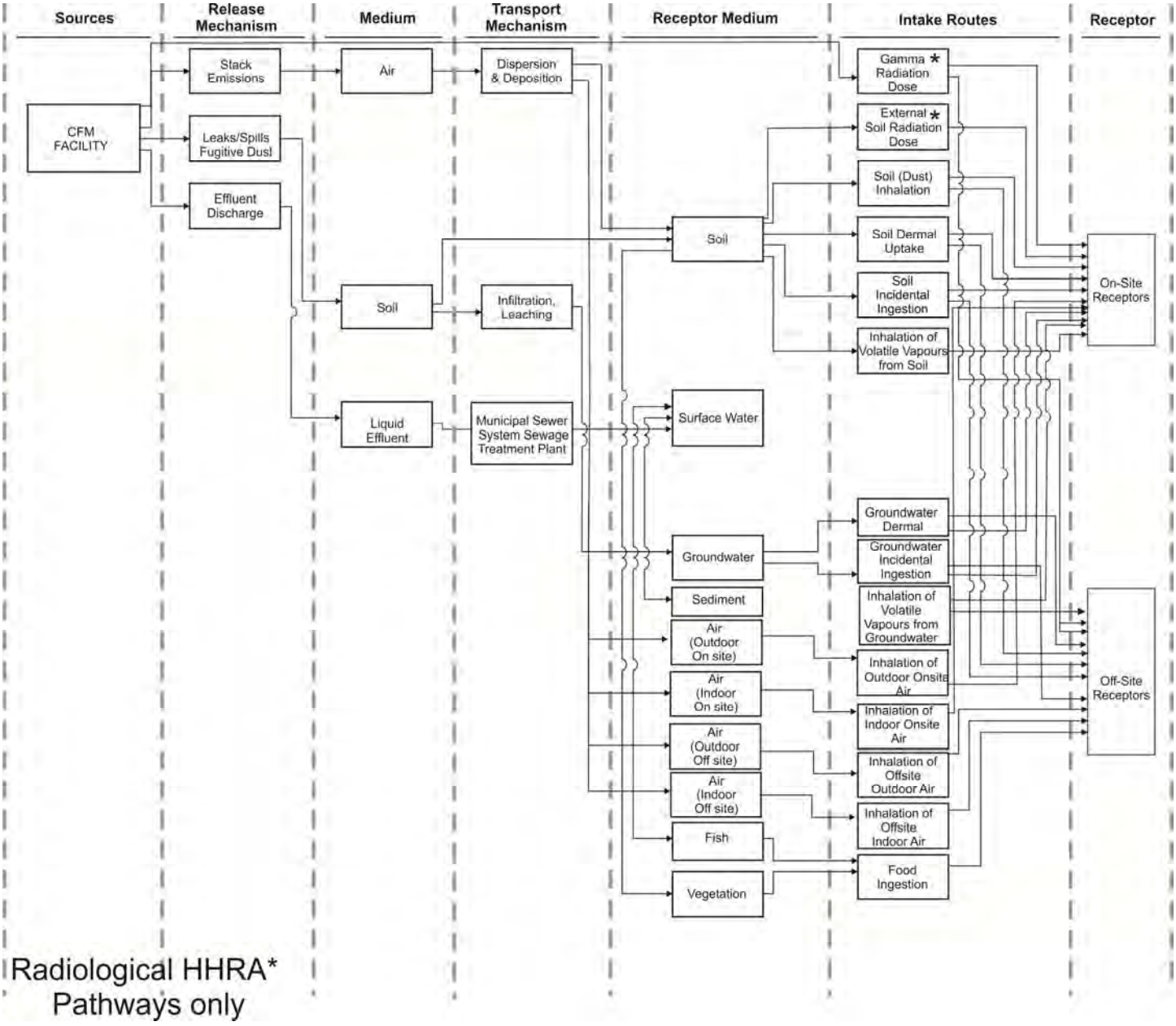


Figure 5.3 HHRA Conceptual Site Model: On-Site Worker Receptors

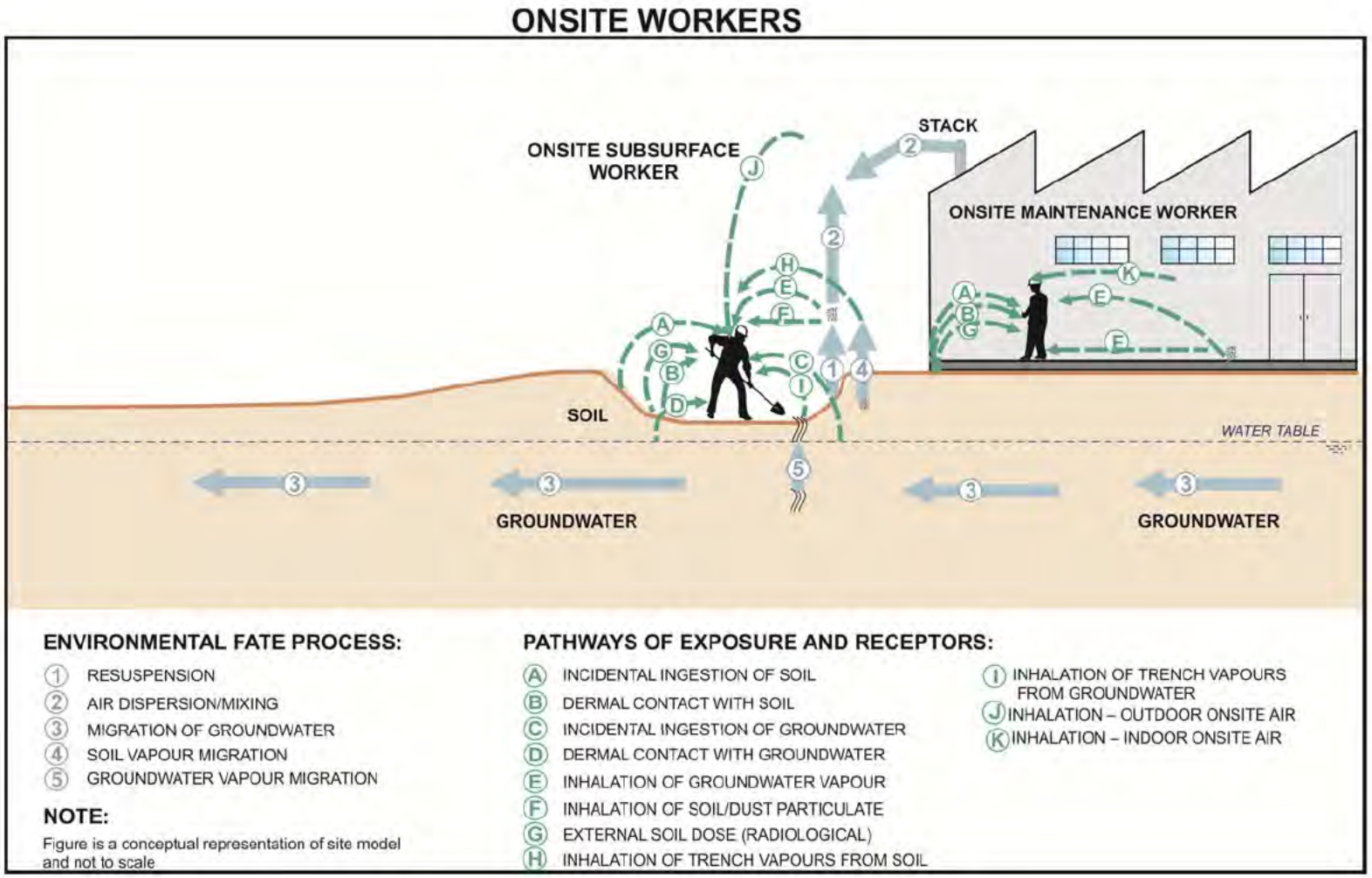
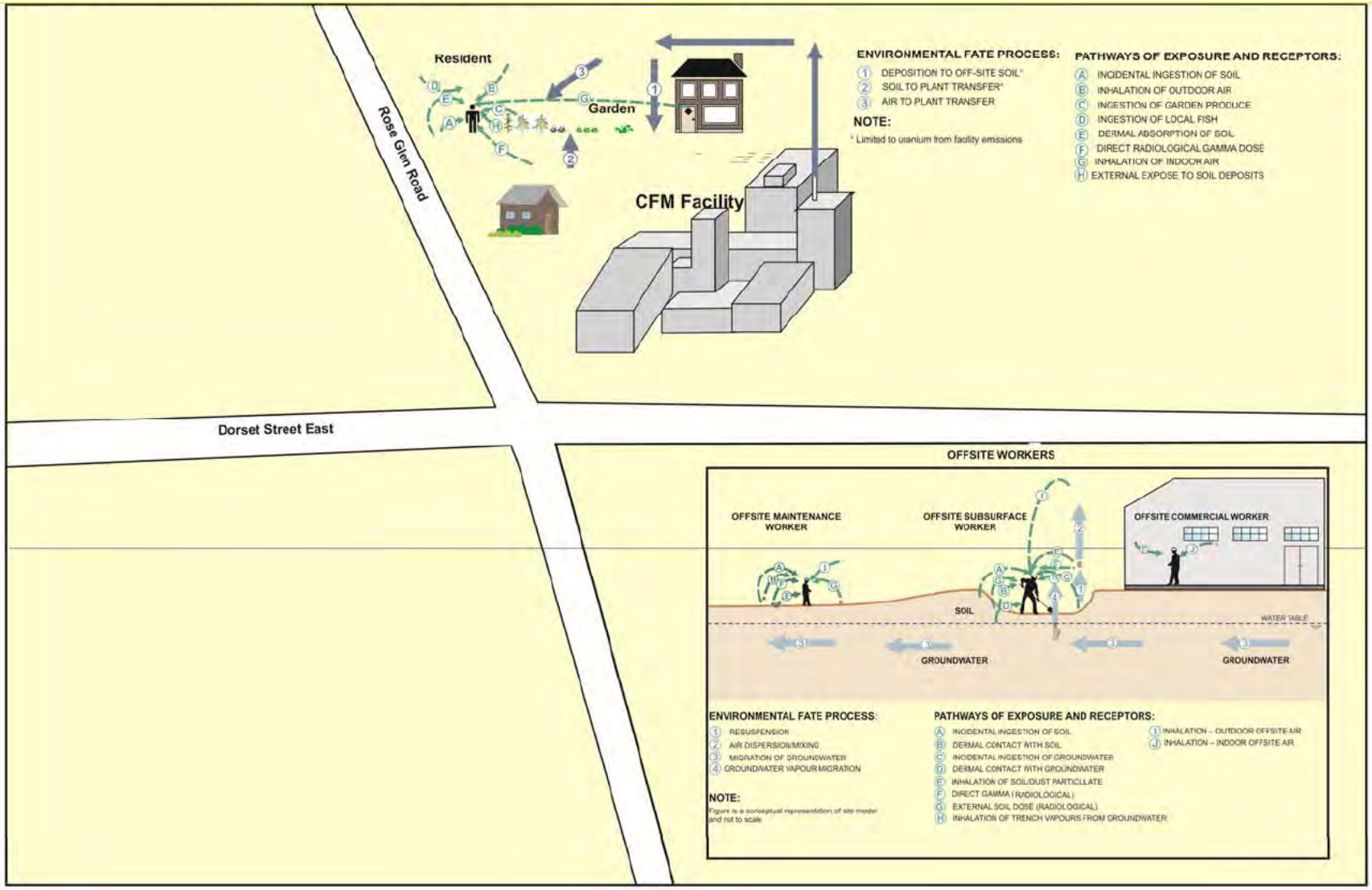


Figure 5.4 HHRA Conceptual Site Model: Off-Site Member of the Public Receptors



Problem Formulation Checklist

Table 5.3 presents the problem formulation checklist for the HHRA, consistent with CSA (2012).

Table 5.3 HHRA – Problem Formulation Checklist

(See Sections 5.1.1 and 5.1.3 for further discussion)

a) Land Use

Land Use		
X	*Agricultural*	No agricultural land use identified within study area.
✓	*Residential*	Residential land is identified immediately adjacent to the facility.
✓	*Commercial*	Commercial land is identified immediately adjacent to the facility.
✓	*Industrial*	Facility site and some immediately adjacent lands identified as industrial.
X	*Parkland*	Park land not applicable to study area.

b) Receptor Groups

Receptor Groups		
✓	*Public*	Members of the public, including nearby residents, represented in the study.
✓	*Employees*	Facility workers included in the study.
✓	*Construction*	Construction worker receptors not specified, however off-site worker activities/duties include soil sub-surface activities in order to address soil exposures (See Table 5.1 and Table 5.2).
X	*First Nations*	No First Nations groups identified within the study area.

c) Critical Receptors

Critical Receptors		
✓	*Infant*	Worker receptors are assumed to be adults only. Public receptors include all 5 recommended age groups for non-radiological HHRA and 3 recommended age groups for radiological HHRA (CSA 2012).
✓	*Toddler*	
✓	*Child*	
✓	*Teen*	
✓	*Adult*	

d) Exposure Pathways

Exposure Pathways		
✓	*Incidental Soil Ingestion*	Included for relevant receptors (Receptors 1, 2, 4, 5, 6 and 7)
✓	*Soil dermal absorption*	Included for relevant receptors (Receptors 1, 2, 4, 5, 6 and 7)
✓	*Soil dust inhalation*	Included for relevant receptors (Receptors 1, 2, 4, 5, 6 and 7)
✓	*Soil vapour inhalation*	Included for relevant receptors (Receptors 2 and 7)
✓	*Groundwater incidental ingestion*	Included for relevant receptors (Receptors 2, 5 and 7)
✓	*Groundwater dermal absorption*	Included for relevant receptors (Receptors 2, 5 and 7)
✓	*Groundwater vapour inhalation*	Included for relevant receptors (Receptors 2, 5 and 7)
X	*Drinking water ingestion*	Not applicable (see Section5.1.3.6)
X	*Surface water incidental ingestion*	Not applicable (see Section 5.1.3.6)
X	*Surface water dermal absorption*	Not applicable (see Section 5.1.3.6)
✓	*Ingestion of local fish*	Included for resident receptors (Receptors 6 and 7)
✓	*Ingestion of garden produce*	Included for resident receptors (Receptors 6 and 7)
X	*Ingestion of wild game*	Not applicable (see Section 5.1.3.6)
✓	*Air inhalation*	Included for all receptors
✓	*External soil radiation dose (by area)*	Included for all receptors
X	*External radiation dose from immersion in surface water*	Not applicable (see Section 5.1.3.6)
X	*External radiation dose from immersion in air*	Excluded (see Section 5.1.3.6)
✓	*Direct gamma radiation dose*	Included for all receptors

5.2 Exposure Assessment

5.2.1 Exposure Locations

The environmental media that a given human receptor is exposed to differs based on their location. For example, both worker and public receptors have the potential for exposure to soil, but the soil that a worker receptor is exposed to is different than the soil that a public receptor is exposed to, since these receptors occupy different locations.

Table 5.4 provides a tabular outline of each human receptor, the assessment areas they are associated with, and the corresponding environmental media they may be exposed to, based on the descriptions of the receptors and their behaviours presented in Table 5.1 (for worker receptors, this includes the nature of their duties).

For groundwater, exposure is limited to trench digging by sub-surface workers both on and off-site. Surface water exposure is limited to fish ingestion by residents.

Table 5.4 Human Receptors, Exposure Media, and Method of Assessment

Receptor	Location	Pathway	Exposure Media	Method of Assessment
Maintenance Worker	*Onsite*	Inhalation	Air - Indoor	Assess inhalation using measured onsite indoor air data. Conservative, since measured indoor air concentrations are greater than modelled fenceline outdoor air concentrations; and, measured indoor air concentrations implicitly include contributions from soil and groundwater vapours.
			Soil Vap. (onsite, non-rad only)	Implicitly included in indoor air inhalation exposure (above) through the use of measured total indoor air concentration data.
		Dermal Incidental Ingestion Inhalation (dust)	Soil – Onsite	Assess using measured on-site soil data.
Sub-Surface Worker	*Onsite*	Inhalation	Air - Outdoor	Assess inhalation exposure using modelled fenceline outdoor air concentrations. Exposure to indoor air is addressed via Maintenance Worker receptor inhalation (above).
		Dermal Incidental Ingestion Inhalation (dust) Inhalation (soil trench vap., non-rad only)	Soil - Onsite	Assess using measured on-site soil data. Exposure to soil vapours is assessed using modelled soil-trench-vapour concentrations. Confined trench space allows vapours to accumulate and exposure to trench vapour typically bounds exposure to other indoor vapour.
		Dermal Incidental Ingestion Inhalation (GW trench vap., non-rad only)	GW - Onsite	Assess using measured on-site groundwater data. Exposure to groundwater vapours is assessed using modelled groundwater-trench-vapour concentrations. Confined trench space allows vapours to accumulate and exposure to trench vapour typically bounds exposure to other indoor vapour.
Commercial Worker	*Offsite*	Inhalation	Air - Indoor Offsite	Assess using measured offsite indoor air data. Measured indoor air concentrations implicitly include contributions from soil and groundwater vapours.
			Offsite GW Vap. (non-rad only)	Implicitly included in indoor air inhalation exposure (above) through the use of measured total indoor air concentration data.
Maintenance Worker	*Offsite*	Inhalation	Air - Outdoor	Assess using modelled fenceline outdoor air. Receptor is located outdoors.
		Inhalation (Dust) Dermal Incidental Ingestion	Soil - Offsite	Assessed using incremental modelled uranium concentrations in offsite soil, based on air emissions (outdoor modelled fenceline 'baseline' concentrations) and soil buildup.
Sub-Surface Worker	*Offsite*	Inhalation	Air - Outdoor	Assess inhalation using modelled fenceline outdoor air concentrations. Receptor is located outdoors.
		Dermal Ingestion Inhalation (dust)	Soil - Offsite	Assessed using incremental modelled uranium concentrations in offsite soil, based on air emissions (outdoor modelled fenceline 'baseline' concentrations) and soil buildup.

Receptor	Location	Pathway	Exposure Media	Method of Assessment
		Dermal Incidental Ingestion Inhalation (GW Trench Vap., non-rad only)	GW - Offsite	Assess using measured offsite GW concentrations, along with GW-trench-vapour modelling results.
Resident	*Offsite*	Inhalation	Air - Indoor/Outdoor	Assess using modelled fenceline outdoor air, assuming no outdoor-to-indoor attenuation (conservative).
		Dermal Incidental Ingestion Produce Ingestion Inhalation (Dust)	Soil - Offsite	Assessed using incremental modelled uranium concentrations in offsite soil, based on air emissions (outdoor modelled fenceline 'baseline' concentrations) and soil buildup.
		Fish ingestion	Surface Water - Harbour	Assess using concentrations of uranium in STP effluent at the point of discharge to Lake Ontario, plus a dilution factor to account for dilution occurring over the distance to harbour (where receptor fishing activities occur).
Resident & Sub.Surf Worker	*Offsite*	Inhalation	Air - Indoor/Outdoor	Assess using modelled fenceline outdoor air, assuming no outdoor-to-indoor attenuation (conservative).
		Dermal Incidental Ingestion Produce Ingestion Inhalation (dust)	Soil - Offsite	Assessed using incremental modelled uranium concentrations in offsite soil, based on air emissions (outdoor modelled fenceline 'baseline' concentrations) and soil buildup.
		Dermal Incidental Ingestion Inhalation (dust) Inhalation (soil trench vap., non-rad only)	Soil - Onsite	Assess pathways using measured onsite soil data, along with soil-trench-vapour modelling results.
		Dermal Incidental Ingestion Inhalation (GW trench vap., non-rad only)	GW - Onsite	Assess using measured offsite GW concentrations, along with GW-trench-vapour modelling results.
		Fish ingestion	Surface Water - Harbour	Assess using concentrations of uranium in STP effluent at the point of discharge to Lake Ontario, plus a dilution factor to account for dilution occurring over the distance to harbour (where receptor fishing activities occur).

5.2.1.1 Exposure Factors, Durations & Frequencies

Table 5.5 presents the exposure factors for the HHRA (both non-radiological and radiological). Intake rates for fish, and backyard produce are taken from N288.1-14. References and brief rationale for each particular value are provided in the table.

Table 5.6 presents the exposure durations for the HHRA.

Table 5.5 HHRA Exposure Factors & Durations

a) Non-Radiological HHRA Exposure Factors *(HC (2010a) unless otherwise noted; consistent with CSA (2012))*

Age Group[a]	Infant	Toddler	Child	Teen	Adult	Worker
Exposure Factors						
Age	0-6 months	7 months – 4 years	5-11 years	12-19 years	≥ 20 years	≥ 20 years
Age group duration (yrs)	0.5	4-5	7	8	61	30
Averaging time for carcinogens (yrs)	80	80	80	80	80	56
Body weight (kg)	8.2	16.5	32.9	59.7	70.7	70.7
Inhalation Rate (m^3/d)	2.2	8.3	14.5	15.6	16.6	1.4 m^3/hr
Exposed skin area – soil (hands & arms) (cm^2)	870	1,320	2,070	3,030	3,390	3,390
Incidental Soil Ingestion Rate (g/d)	0.02	0.08	0.02	0.02	0.02	0.1
Soil Loading (g/cm^2/event)	0.0001	0.0001	0.0001	0.0001	0.0001	0.001
Dermal event (ev)	1	1	1	1	1	1
Incidental Groundwater Ingestion Rate (L/d) [b]	0	0	0	0	0	0.01
Food - Local Fractions & Intakes						
Fish - Total Ingestion Rate[c] (g/d)	0	56	90	104	111	0
Fish - Local Fraction	*0.1*					
Fish – Local Ingestion Rate (g/d)	0	5.6	9	10.4	11.1	0
Produce – Total Ingestion Rate (g/d)[d]	0	172	259	347	325	0
Produce – Local Fraction	*0.25 (most conservative in CSA (2014), following CSA (2012))*					
Produce – Local Ingestion Rate (g/d)	0	43	65	87	81	0

Notes:
[a] In the radiological assessment, three age groups were considered based on CSA (2014); these age groups correspond to the Infant, Child and Adult age groups presented above.
[b] Assumed.
[c] HC (2004) PQRA Guidance.
[d] HC (2010a) PQRA, values for root vegetables plus other vegetables. Assumed 0 backyard produce ingestion for infant.

b) Radiological HHRA Exposure Factors

Age Group[a]	Infant	Child	Adult	Ref.
Exposure Factors				
Age	0-5 years	6-15 years	16-70 years	CSA (2014) N288.1 – Following N288.6
Inhalation Rate (m^3/hr)	0.31	0.89	0.96	CSA (2014) N288.1 – Following N288.6
Incidental Soil Ingestion Rate (g/d)	0.204	0.185	0.02	CSA (2014) N288.1 – Following N288.6
Food - Local Fractions & Intakes				
Fish - Total Ingestion Rate (g/d)	6.4	18.5	28.1	CSA (2014) N288.1 – Table G.9c (90th percentile energy expenditures) – Following N288.6
Fish - Local Fraction	1	1	1	CSA (2014) N288.1 – Table G.9c (90th percentile energy expenditures) – Following N288.6
Fish - Local Ingestion Rate (g/d)	*Product of Total Ingestion Rate multiplied by Local Fraction*			
Produce - Total Ingestion Rate (g/d)	342	726	1131.7	CSA (2014) – Following N288.6 for fruit and berries, vegetables, and potatoes
Produce - Local Fraction	0.25	0.25	0.25	CSA (2014) – Following N288.6 for fruit and berries, vegetables, and potatoes.
Produce - Local Ingestion Rate (g/d)	*Product of Total Ingestion Rate multiplied by Local Fraction*			

Table 5.6 HHRA Exposure Durations

a) Overall Exposure Time

Receptor#	Receptor	Exposure Durations/Frequencies
0	Onsite Industrial Worker	Full time CFM NEW (8 hrs/day, 5 days/wk, 50 wks/yr) on site, indoors. Balance of the year outside the study area. As discussed in Table 5.1, NEWs are beyond the scope of N288.6 and are not assessed further in this ERA.
1	Onsite Maintenance Worker	Contractor (8 hrs/day, 5 days/wk, 2 wks/yr) on site, 100% indoors. Exposure to soil occurs throughout this occupational period (i.e. for 2 wk). Balance of the year outside the study area.
2	Onsite Sub-Surface Worker	Contractor (8 hrs/day, 5 days/wk, 2 wks/yr) on site, 100% outdoors. Two week exposure period is spent in a trench deep enough to reach groundwater; in which time direct contact exposure would be bound by a maximum of 4 hours per day. Exposure to soil also occurs for the duration of this occupation period (i.e. for the 8 hrs/day, 5 days/wk, 2 wk/yr). Balance of the year outside the study area.
3	Offsite Commercial Worker	Full time offsite worker (8 hrs/day, 5 days/wk, 50 wks/yr) in buildings near the CFM facility; indoors. Balance of the year outside the study area.
4	Offsite Maintenance Worker	Full time employee (8 hrs/day, 5 days/wk, 50 wks/yr) off site adjacent to the facility, outdoors. Exposure to soil occurs for the duration of this occupational period. Balance of the year outside the study area.
5	Offsite Sub-Surface Worker	Contractor, present for 1 week of the year (8 hrs/day, 5 days/wk, 1 wk/yr) off-site, adjacent to the CFM facility in an outdoor trench deep enough to reach groundwater; in which time direct (contact) exposure would be bound by a maximum of 4 hours. Exposure to offsite soil occurs for the duration of this occupational period (i.e. for 8 hr/d, 5 d/wk, 1 wk/yr). Balance of the year outside the study area.
6	Resident	Spends the entire year in the study area, in a residence located off site to the west or north of the CFM facility. Occupancy is assumed to be indoors, aside from gardening activities, during which exposure to soil occurs for 2 hr/day, 7 days/wk, 52 wks/yr.
7	Resident & Onsite Subsurface Worker	Resident and On Site Subsurface Worker. Spends entire year in the study area. Combined exposure factors of the Resident (offsite soil, air) as well as the onsite Subsurface Worker (onsite soil, air, and groundwater).

b) Exposure Durations & Frequencies for HHRA

Receptor No.	Receptor Name	Time-based Exposures	Associated Activities	Pathways	Units	Infant	Toddler	Child	Teen	Adult
0	Industrial On-Site Worker	Time spent exposed to air	Indoors	*Inhalation*	*(h/d)*					8
					(d/week)					5
					(weeks/y)					50
		Gamma exposure**	-	*Direct Gamma*	*(h/d)*					8
					(d/week)					5
					(weeks/y)					50
		Exposure Duration (y)								30
		Averaging Time (y)		*Carcinogens*						56
				Non-carcinogens						1
1	Maintenance On-Site Worker	Time spent exposed to soil*	Indoors*/ Outdoors	*Dermal Uptake Inc. Ingestion Dust Inhalation*	*(h/d)*					8
					(d/week)					5
					(weeks/y)					2
		Time spent exposed to air*	Indoors*	*Inhalation**	*(h/d)*					8
					(d/week)					5
					(weeks/y)					2
		Gamma exposure**	-	*Direct Gamma*	*(h/d)*					8
					(d/week)					5
					(weeks/y)					2
		Exposure Duration (y)								30
		Averaging Time (y)		*Carcinogens*						56
				Non-carcinogens						1
2	Sub-surface On-Site Worker	Time spent exposed to soil	Indoor/ Outdoor	*Dermal Uptake Inc. Ingestion Dust Inhalation*	*(h/d)*					8
					(d/week)					5
					(weeks/y)					2
		Time spent exposed to soil vapours	Trench	*Vap. Inhalation (Non-rad only)*	*(h/d)*					8
					(d/week)					5
					(weeks/y)					2
		Time spent exposed to groundwater vapours	Trench	*Vap. Inhalation (Non-rad only)*	*(h/d)*					8
					(d/week)					5
					(weeks/y)					2
		Time spent exposed to groundwater	Indoor/Outdoor	*Dermal Uptake Inc. Ingestion*	*(h/d)*					4
					(d/week)					5
					(weeks/y)					2
		Time spent exposed to air	Outdoor	*Inhalation*	*(h/d)*					8

Receptor No.	Receptor Name	Time-based Exposures	Associated Activities	Pathways	Units	Infant	Toddler	Child	Teen	Adult
					(d/week)					5
					(weeks/y)					2
		Gamma exposure**	-	***Direct Gamma***	*(h/d)*					8
					(d/week)					5
					(weeks/y)					2
		Exposure Duration (y)								30
		Averaging Time (y)		*Carcinogens*						56
				Non-carcinogens						1
3	Commercial Off-Site Worker	Time spent exposed to air*	**Indoors***	***Inhalation****	*(h/d)*					8
					(d/week)					5
					(weeks/y)					50
		Gamma exposure**	-	***Direct Gamma***	*(h/d)*					8
					(d/week)					5
					(weeks/y)					50
		Exposure Duration (y)								30
		Averaging Time (y)		*Carcinogens*						56
				Non-carcinogens						1
4	Maintenance Off-site Worker	Time spent exposed to soil	**Outdoors**	***Dermal Inc. Ingestion Dust Inhalation***	*(h/d)*					8
					(d/week)					5
					(weeks/y)					50
		Time spent exposed to air	**Outdoors**	***Inhalation***	*(h/d)*					8
					(d/week)					5
					(weeks/y)					50
		Gamma exposure**	-	***Direct Gamma***	*(h/d)*					8
					(d/week)					5
					(weeks/y)					50
		Exposure Duration (y)								30
		Averaging Time (y)		*Carcinogens*						56
				Non-carcinogens						1
5	Subsurface Off-Site Worker	Time spent exposed to soil	**Outdoors**	***Dermal Inc. Ingestion Dust Inhalation***	*(h/d)*					8
					(d/week)					5
					(weeks/y)					1
		Time spent exposed to groundwater	**Outdoors**	***Dermal Contact Inc. Ingestion***	*(h/d)*					4
					(d/week)					5
					(weeks/y)					1

Receptor No.	Receptor Name	Time-based Exposures	Associated Activities	Pathways	Units	Infant	Toddler	Child	Teen	Adult
		Time spent exposed to groundwater vapours	**Trench**	***Vap. Inhalation***	*(h/d)*					8
					(d/week)					5
					(weeks/y)					1
		Time spent exposed to air	**Outdoors**	***Inhalation***	*(h/d)*					8
					(d/week)					5
					(weeks/y)					1
		Gamma exposure**	**-**	***Direct Gamma***	*(h/d)*					8
					(d/week)					5
					(weeks/y)					1
		Exposure Duration (y)								30
		Averaging Time (y)		*Carcinogens*						56
				Non-carcinogens						1
6	Resident	Time spent exposed to soil	**Outdoors**	***Dermal Inc. Ingestion Dust Inhalation***	*(h/d)*	2	2	2	2	2
					(d/week)	7	7	7	7	7
					(weeks/y)	52	52	52	52	52
		Time spent exposed to air	**Indoors/ Outdoors**	***Inhalation (Non-rad)***	*(h/d)*	24	24	24	24	24
					(d/week)	7	7	7	7	7
					(weeks/y)	52	52	52	52	52
		Time spent exposed to air	**Indoors**	***Inhalation (Rad)***	*(h/d)*	22	22	22	22	22
					(d/week)	7	7	7	7	7
					(weeks/y)	52	52	52	52	52
		Time spent exposed to air	**Outdoors**	***Inhalation (Rad)***	*(h/d)*	2	2	2	2	2
					(d/week)	7	7	7	7	7
					(weeks/y)	52	52	52	52	52
		Gamma exposure**	**-**	***Direct Gamma***	*(h/d)*	24	24	24	24	24
					(d/week)	7	7	7	7	7
					(weeks/y)	52	52	52	52	52
		Exposure Duration (y)				0.5	4.5	7	8	61
		Averaging Time (y)		*Carcinogens*		80	80	80	80	80
				Non-Carcinogens		1	1	1	1	1
7	Resident + Worker	Time spent exposed to onsite soil	**Indoors/ Outdoors**	***Dermal Uptake Inc. Ingestion Dust Inhalation***	*(h/d)*					8
					(d/week)					5
					(weeks/y)					2
		Time spent exposed to onsite soil vapours	**Trench**	***Vap. Inhalation***	*(h/d)*					8
					(d/week)					5
					(weeks/y)					2

Receptor No.	Receptor Name	Time-based Exposures	Associated Activities	Pathways	Units	Infant	Toddler	Child	Teen	Adult
		Time spent exposed to offsite soil	Outdoors	***Dermal Uptake Inc. Ingestion Dust Inhalation***	*(h/d)*					2
					(d/week)					7
					(weeks/y)					52
		Time spent exposed to onsite groundwater	Indoors/ Outdoors	***Dermal Uptake Inc. Ingestion***	*(h/d)*					4
					(d/week)					5
					(weeks/y)					2
		Time spent exposed to onsite groundwater vapours	Trench	***Vap. Inhalation***	*(h/d)*					8
					(d/week)					5
					(weeks/y)					2
		Time spent exposed to air	Indoors/ Outdoors	***Inhalation (Non-rad)***	*(h/d)*					24
					(d/week)					7
					(weeks/y)					52
		Time spent exposed to air	Indoors (off-site)	***Inhalation (Rad)***	*(h/d)*					9.29
					(d/week)					7
					(weeks/y)					52
		Time spent exposed to air	Outdoors	***Inhalation (Rad)***	*(h/d)*					2
					(d/week)					7
					(weeks/y)					52
		Offsite Gamma exposure**	-	***Direct Gamma***	*(h/d)*					2
					(d/week)					7
					(weeks/y)					52

* Inhalation assessed using measured indoor air concentrations, which implicitly include contributions from soil and groundwater vapours.

** Radiological only

5.2.2 Exposure Point Concentrations (Levels)

As outlined in Table 5.4, there are many different environmental media that human receptors could potentially be exposed to. The following tables present the concentrations (or dose rates, for gamma) that are associated with the various environmental media. These summary statistics are used as exposure point concentrations in subsequent exposure calculations.

Since the primary pathway of exposure to surface water in the HHRA is via ingestion of fish caught near the Port Hope harbour, surface water concentrations used in human health risk calculations are estimated for the harbour by applying a dilution factor of 2090x (see Section 3.4.2) to the CFM effluent concentration from the Cameco (2015a) *2014 ACMOPR*. This is conservative because the Cameco (2015a) sewer effluent concentrations represent the concentration in CFM effluent released into the sewer system, whereas the concentration of sewer effluent actually released from the lake outfall would be further diluted by the effluents from other contributors.

5.2.2.1 Non-Radiological

For Tier 1 exposure calculations, the maximum concentration in any particular environmental medium is used, regardless of its location (with the exception of surface water, as discussed above in Section 5.2.2).

It is important to note that in general, human receptors located onsite are exposed to concentrations of COPCs in onsite media (soil, air, and groundwater). Conversely, human receptors located offsite are exposed to concentrations of COPCs in offsite media. The exception to this distinction is the 'Resident & Worker' receptor, which receives the exposure as an offsite resident receptor (to offsite media), as well as the exposure of an onsite subsurface worker (to onsite media).

Tier 1 concentrations of COPCs in environmental media are shown in Table 5.7, whereas Tier 1 concentrations of COPCs in ingested food items (based on their corresponding concentrations in respective environmental media) are shown in Table 5.8. Tier 2 concentrations in environmental media are shown in Table 5.9

Table 5.7 HHRA – Tier 1 COPC Concentrations in Environmental Media

COPC	Air Concentration - Outdoor ($\mu g/m^3$)	Notes / Reference
U	0.00122	Maximum modelled outdoor fenceline concentration (Table 3.1).
COPC	**Air Concentration – Indoor; Offsite ($\mu g/m^3$)**	**Notes / Reference**
U	0.00061	Assumed to be 50% of modelled outdoor fenceline concentration
1,1-DCE	<0.20	Analytical results from sample collected November 2011.
cis-1,2-DCE	<0.20	
trans-1,2-DCE	<0.20	
TCE	0.32	
VC	<0.051	
TCA	ND	No Data
Chloroethane		
PCE		
COPC	**Air Concentration – Indoor; Onsite ($\mu g/m^3$)**	**Notes / Reference**
U	7	Max. room average (Cameco 2015a, Table 20)
1,1-DCE	<0.20	Maximum measured concentration among samples collected June 2012.
cis-1,2-DCE	0.98	
trans-1,2-DCE	<0.20	
TCE	23	
VC	0.097	
TCA	ND	No Data
Chloroethane		
PCE		
COPC	**Soil Concentration - Offsite (mg/kg DW)**	**Notes / Reference**
U	0.05	Incremental soil concentration, based on maximum fenceline air concentration (above), and soil deposition modelling (Section 3.2).
COPC	**Soil Concentration - Onsite (mg/kg DW)**	**Notes / Reference**
U	17.4	Cameco (2015a); max measured onsite soil conc
1,1-DCE	<0.002	Aqua Terre (2009); Max measured value (<MDL)
cis-1,2-DCE	<0.002	Aqua Terre (2009); Max measured value among DCE variants (all <MDL)
trans-1,2-DCE	<0.002	Aqua Terre (2009); Max measured value (<MDL)
TCE	0.003	Aqua Terre (2009); Max measured value
VC	0.0025	Aqua Terre (2009); Max measured value (<MDL), plus degradation of TCE and PCE.
TCA	0.0025	Aqua Terre (2009); Max measured value (<MDL), plus degradation of TCE and PCE.
Chloroethane	0.0005	Aqua Terre (2009); No measured data, based on degradation of TCE and PCE.
PCE	<0.002	Aqua Terre (2009); Max measured value (<MDL)

COPC	Surface Water Concentration (µg/L)	Notes / Reference
U	0.0244	Cameco (2015a); CFM annual average sewer effluent uranium concentration of 0.051 mg/L from 2014 (calculated from Table 29), with dilution factor of 2090x to account for dilution over distance from STP outfall to harbour (Section 3.4.2)
COPC	**Groundwater Concentration - Onsite (mg/L)**	**Notes / Reference**
Uranium	0.788	SNC (2015a); Maximum measured value
1,1-DCE	0.0829	SNC (2015b); Maximum measured value
cis-1,2-DCE	0.804	SNC (2015b); Maximum measured value among DCE variants
trans-1,2-DCE	0.115	SNC (2015b); Maximum measured value
TCE	226	SNC (2015b); Maximum measured value
VC	22.8274	SNC (2015b); Maximum measured value, plus degradation of TCE and DCE.
TCA	22.7994	SNC (2015b); Maximum measured value, plus degradation of TCE and DCE.
Chloroethane	27.6804	SNC (2015b); Maximum measured value (<MDL), plus degradation of TCE and DCE.
PCE	0.114	SNC (2015b); Maximum measured value
COPC	**Groundwater Concentration - Offsite[a] (mg/L)**	**Notes / Reference**
Uranium	0.0065	SNC (2015a); Maximum measured value
1,1-DCE	0.0012	SNC (2015b); Maximum measured value
cis-1,2-DCE	0.132	SNC (2015b); Maximum measured value among DCE variants
trans-1,2-DCE	0.019	SNC (2015b); Maximum measured value
TCE	1.19	SNC (2015b); Maximum measured value
VC	0.2729	SNC (2015b); Maximum measured value, plus degradation of TCE and DCE.
TCA	0.1329	SNC (2015b); Maximum measured value, plus degradation of TCE and DCE.
Chloroethane	0.1332	SNC (2015b); Maximum measured value, plus degradation of TCE and DCE.
PCE	0.0005	SNC (2015b); Maximum measured value

COPC	Air Concentration - Onsite-GW-Trench ($\mu g/m^3$)	Notes / Reference
1,1-DCE	0.26	Trench-vapour concentrations based on onsite groundwater concentrations (above), modelled using MOE 2011b & ASTM 1995 methodologies. See Section 3.3.
cis-1,2-DCE	0.29	
trans-1,2-DCE	0.096	
TCE	210	
VC	93	
TCA	37	
Chloroethane	90	
PCE	0.17	
COPC	**Air Concentration - Offsite-GW-Trench ($\mu g/m^3$)**	**Notes / Reference**
1,1-DCE	0.0037	Trench-vapour concentrations based on offsite groundwater concentrations (above), modelled using MOE 2011b & ASTM 1995 methodologies. See Section 3.3.
cis-1,2-DCE	0.048	
trans-1,2-DCE	0.016	
TCE	1.1	
VC	1.1	
TCA	0.22	
Chloroethane	0.43	
PCE	7.2E-04	
COPC	**Air Concentration - Onsite-Soil-Trench ($\mu g/m^3$)**	**Notes / Reference**
1,1-DCE	7.88E-05	Trench-vapour concentrations based on onsite soil concentrations (above), modelled using MOE 2011b & ASTM 1995 methodologies. See Section 3.3.
cis-1,2-DCE	1.88E-04	
trans-1,2-DCE	1.39E-04	
TCE	2.26E-04	
VC	8.08E-05	
TCA	1.38E-04	
Chloroethane	1.55E-05	
PCE	1.49E-04	

Note:

[a] offsite groundwater wells based on SNC (2015).

Table 5.8 HHRA – Tier 1 COPC Concentrations in Dietary Intakes

COPC	Produce Concentration (mg/kg FW)	Notes / Reference
U	6.06E-03	Soil-to-Plant: TF=0.01 kg/kg dw (Table G.3, CSA 2014) with incremental offsite soil uranium concentration (Table 5.7) and an assumed moisture content of 81%. Air-to-Plant: TF=4890 m^3/kg fw (Table A.5a for generic fruits and vegetables, CSA 2014) with maximum fenceline air concentration (Table 5.7). Produce concentrations calculated as the sum of contributions from soil and air.
COPC	**Fish Concentration (mg/kg FW)**	**Notes / Reference**
U	2.34E-05	TF=0.96 L/kg fw: (Table A.25a, CSA 2014) with harbour surface water uranium concentration (Table 5.7)

Table 5.9 HHRA – Tier 2 COPC Concentrations in Environmental Media

COPC	Indoor Air Concentration - Onsite[a] ($\mu g/m^3$)	Notes / Reference
U	3	Overall average of all in-plant air samples (Cameco 2015a)
COPC	**Groundwater Concentration - Offsite[a] (mg/L)**	**Notes / Reference**
TCE	0.309	95% UCLM among offsite wells.
VC	0.0859	95th percentile concentration of VC among offsite wells, plus degradation. *(Insufficient number of measured results to calculate a meaningful 95%UCLM)*
COPC	**Groundwater Concentration - Onsite (mg/L)**	**Notes / Reference**
TCE	30.62	95% UCLM among onsite wells.
VC	3.072	95% UCLM concentration of VC among onsite wells, plus degradation.
COPC	**Groundwater Vapour Concentration - Offsite[a] ($\mu g/m^3$)**	**Notes / Reference**
TCE	0.29	Trench-vapour concentrations based on Tier 2 offsite groundwater concentrations (above); modelled using MOE 2011b & ASTM 1995 methodologies - see Section 3.3.
VC	0.35	
COPC	**Groundwater Vapour Concentration - Onsite ($\mu g/m^3$)**	**Notes / Reference**
TCE	28.92	Trench-vapour concentrations based on Tier 2 onsite groundwater concentrations (above); modelled using MOE 2011b & ASTM 1995 methodologies - see Section 3.3.
VC	12.56	

Note:
[a] offsite vs. onsite groundwater wells based on SNC (2015a, 2015b).

5.2.2.2 Radiological

For Tier 1 exposure calculations, the maximum concentration in any particular environmental medium is used, regardless of its particular location. Since the CFM facility receives clean/pure uranium material, it is assumed that only U-238, U-234, and U-235 are present (i.e. further decay products are not included).

Since direct radionuclide measurement data are not available, the levels of radionuclides must be inferred from the level of natural uranium (U_{nat}) in sample measurements. The methodology in Lowe (2004) is used to correlate U-238, U-234, and U-235 activity from U_{nat} concentrations. These activities are shown in Table 5.10. Outdoor air concentration is based on the maximum measured concentration among fenceline stations. Indoor off-site air concentrations are assumed to be 50% of the outdoor air concentration. For indoor on-site air concentrations, indoor air measurements are available for several rooms; an average room concentration was calculated for each room, and the highest of the room averages is used.

To assess the external radiation dose from radionuclide contaminants in soil, soil concentrations are evaluated on a surface area basis (Bq/m^2). To assess this pathway, maximum soil levels – which are available on a mass basis in Bq/gDW – are converted from a mass concentration to a volume concentration using a density of 1,600 kg/m^3 following the US NRC (1977) methodology. It was assumed, conservatively, that the contamination was contained with the top 1 cm of soil and using this assumption an activity by surface area was calculated.

$$* Soil\ Conc\ \left(\frac{Bq}{m2}\right) = Soil\ Conc\left(\frac{Bq}{gDW}\right) \times 1000\ (\frac{g}{kg}) \times 1600(\frac{kg}{m^3}) \times 0.01(m)$$

Table 5.10 presents the radionuclide concentrations in environmental media that are used in the Tier 1 HHRA.

Table 5.11 presents the resulting radionuclide concentrations in contaminated foods that are used in the Tier 1 HHRA.

Table 5.10 HHRA – Tier 1 Radionuclide Levels in Environmental Media

(See Table 5.3 and Table 5.4 for discussion on the media, receptors and pathways involved)

Radionuclide	Air Concentration - Outdoor (Bq/m^3)	Notes / Reference
U-234	1.51E-05	Correlated from maximum measured fenceline outdoor air U_{nat} concentration.
U-235	6.94E-07	
U-238	1.51E-05	
Radionuclide	**Air Concentration – Indoor; Offsite (Bq/m^3)**	**Notes / Reference**
U-234	7.53E-06	Assumed to be 50% of outdoor air concentration.
U-235	3.47E-07	
U-238	7.53E-06	
Radionuclide	**Air Concentration – Indoor; Onsite (Bq/m^3)**	**Notes / Reference**
U-234	0.0865	Correlated from the maximum room average U_{nat} concentration – see Table 5.7.
U-235	3.98E-03	
U-238	0.0865	
Radionuclide	**Onsite Soil Concentration (by mass) (Bq/g DW)**	**Notes / Reference**
U-234	0.215	Correlated from maximum measured onsite U_{nat} concentration.
U-235	9.9E-03	
U-238	0.215	
Radionuclide	**Onsite Soil Concentration (by area) (Bq/m^2)**	**Notes / Reference**
U-234	3438.24	Calculated using equation above (US NRC 1977) based on onsite soil concentration (by mass).
U-235	158.41	
U-238	3438.24	
Radionuclide	**Offsite Soil Concentration (by mass) (Bq/g DW)**	**Notes / Reference**
U-234	6.18E-04	Correlated from modelled incremental offsite U_{nat} concentration – see Table 5.7.
U-235	2.85E-05	
U-238	6.18E-04	
Radionuclide	**Offsite Soil Concentration (by area) (Bq/m^2)**	**Notes / Reference**
U-234	9.88	Calculated using equation above (US NRC 1977) based on offsite soil concentration (by mass).
U-235	0.455	
U-238	9.88	
Radionuclide	**Surface Water Concentration (Bq/L)**	**Notes / Reference**
U-234	3.01E-04	Correlated from maximum measured U_{nat} concentration in CFM sewer effluent, with dilution factor of 2090 – see Section 3.4.2.
U-235	1.39E-05	
U-238	3.01E-04	
Radionuclide	**Onsite Groundwater Concentration (Bq/L)**	**Notes / Reference**
U-234	9.73	Correlated from maximum measured onsite Unat concentration.
U-235	0.448	
U-238	9.73	
Radionuclide	**Offsite Groundwater Concentration (Bq/L)**	**Notes / Reference**
U-234	0.080	Correlated from maximum measured offsite Unat concentration.
U-235	0.0037	
U-238	0.080	

Table 5.11 HHRA – Tier 1 Radionuclide Levels in Dietary Intakes

(See Table 5.3 and Table 5.4 for discussion on the media, receptors and pathways involved)

Radionuclide	Fish Concentration (Bq/g FW)	Notes / Reference
U-234	2.89E-07	Correlated from estimated U_{nat} concentration (Table 5.8).
U-235	1.33E-08	
U-238	2.89E-07	
Radionuclide	**Produce Concentration (Bq/g FW)**	**Notes / Reference**
U-234	7.49E-05	Correlated from estimated U_{nat} concentration (Table 5.8).
U-235	3.45E-06	
U-238	7.49E-05	

5.2.3 Radiological Dose Calculation Methods

5.2.3.1 Internal Dose from Inhalation

The radiological dose from inhalation is calculated for each radionuclide using Equation 5-1, based on the methodology from CSA (2012):

$$D_{inh} = IR \times DC_{inh} \times C_{air} \times OF_{i} \quad (5\text{-}1)$$

Where:

D_{inh} = internal radiation dose from inhalation [Sv/yr]

IR = inhalation rate [m^3/yr]

DC_{inh} = inhalation dose coefficient [Sv/Bq]

C_{air} = concentration in air [Bq/m^3]

OF = occupancy factor (fraction of time exposed) [unitless]

5.2.3.2 Internal Dose from Incidental Ingestion of soil

The radiological dose from incidental ingestion of soil is calculated for each radionuclide, following Equation 5-3 (CSA 2012):

$$D_s = I_s \times EF_s \times DC_f \times C_s \quad (5\text{-}3)$$

Where:

D_s = internal radiation dose from incidental ingestion of soil [Sv/yr]

I_s = incidental soil ingestion rate [kg/d]

EF_s = days per year in which the incidental ingestion could occur [d/yr]

DC_f = internal dose coefficient for intake by ingestion [Sv/Bq]

C_s = concentration in soil [Bq/kg]

5.2.3.3 Internal Dose from Ingestion of Contaminated Foods

The radiological dose from ingestion of contaminated food is calculated for each radionuclide, following Equation 5-4 (CSA 2012):

$$D_f = \rho_f \times g_f \times I_f \times DC_f \times C_f \quad (5\text{-}4)$$

Where:

D_f = internal radiation dose from ingestion of contaminated food [Sv/yr]

ρ_f = adjustment factor for food processing (assumed to be 1) [unitless]

g_f = fraction of food from contaminated source (assumed to be 1) [unitless]

I_s = food ingestion rate [kg/yr]

DC_f = internal dose coefficient for intake by ingestion [Sv/Bq]

C_s = concentration in soil [Bq/kg]

5.2.3.4 External dose from contaminated ground deposits

$$Dose_g = f_o \times f_r \times \left[f_u + (1 - f_u) \times S_g\right] \times DC_g \times C_g$$

Where:

f_o = fraction of total time spent by the individual at the exposure location [unitless[

f_r = dose reduction factor to account for non-uniformity of the ground surface [unitless]

f_u = time spent outdoors at the exposure location as a fraction of total time spent at that location [unitless]

S_g = shielding factor for groundshine, or fraction of the outdoor groundshine dose received indoors due to shielding by buildings [unitless]

DC_g = effective dose coefficient for an infinite plane ground deposit [$Sv \cdot a^{-1} \cdot Bq^{-1} \cdot m^2$]

C_g = activity in ground surface [$Bq \cdot m^{-2}$]

5.2.3.5 External Gamma Dose

The dose from exposure to gamma radiation is calculated based on readily-available gamma measurement data from the BRR gamma monitoring program, following Equation 5-6:

$$D_g = DR_g \times D_1 \times D_2 \quad (5\text{-}6)$$

Where:

D_g = external gamma radiation dose [µSv/yr]

DR_g = measured gamma dose rate [µSv/hr]

D_1 = hours per day over which the exposure occurs [hr/d]

D_2 = days per year over which the exposure occurs [d/yr]

5.2.4 Dose Coefficients

Radiological assessment involves the use of dose coefficients (DCs) that convert activity concentrations of radionuclides in environmental media or in the body into radiation doses to human receptors. In the case of external exposure to gamma radiation, on-site monitoring measurements were used.

The DCs used in the radiological HHRA calculations were selected from literature references using the following hierarchy, consistent with CSA (2012).

1. *Worker Receptors (non-NEWs; onsite or offsite) (See Section 5.1.1)*
    a. ICRP 68 (1994): internal dose coefficients
    b. US EPA (1993b): external dose coefficients (GW)
2. *Off-Site Member of the Public Receptors (See Section 5.1.1):*
    a. CSA N288.1 (2014): internal and external dose coefficients; and
    b. ICRP 72 (1995): internal and external dose coefficients.

Table 5.12 summarizes the DCs that were selected for the HHRA calculations.

Table 5.12 HHRA – Dose Coefficients

(a) On-Site Worker Receptors

Radionuclide	Inhalation* (Internal) Sv/Bq	Ref
U-234	8.5E-06	ICRP 68 (1994)
U-235	7.7E-06	ICRP 68 (1994)
U-238	7.3E-06	ICRP 68 (1994)
Radionuclide	**Ingestion (Internal) Sv/Bq**	**Ref**
U-234	4.9E-08	ICRP 68 (1994)
U-235	4.6E-08	ICRP 68 (1994)
U-238	4.4E-08	ICRP 68 (1994)
Radionuclide	**Immersion in Water (External) Sv/yr per Bq/L**	**Ref**
U-234	5.52E-10	US EPA 1993b, Table III.2 (converted)
U-235	5.01E-07	US EPA 1993b, Table III.2 (converted)
U-238	2.51E-10	US EPA 1993b, Table III.2 (converted)
Radionuclide	**External Soil Ground Source (Planer) (External) Sv/yr per Bq/m^2**	**Ref**
U-234	2.36E-11	US EPA 1993b, Table III.2 (converted)
U-235	4.67E-09	US EPA 1993b, Table III.2 (converted)
U-238	1.74E-11	US EPA 1993b, Table III.2 (converted)

Notes:

* Inhalation DCs for 1 µm particle size, Type-S (Slow Absorption).

(b) Off-Site Member of the Public Receptors

Radionuclide	Effective Dose Coefficients for Ingestion (in Sv/Bq)			
	Infant	Child	Adult	Ref
U-234	1.3E-07	7.4E-08	4.9E-08	CSA N288.1 (2014), Table C.2
U-235	1.3E-07	7.1E-08	4.7E-08	CSA N288.1 (2014), Table C.2
U-238	1.2E-07	6.8E-08	4.5E-08	CSA N288.1 (2014), Table C.2
Radionuclide	**Effective Dose Coefficients for Inhalation (in Sv/Bq)**			
	Infant	**Child**	**Adult**	**Ref**
U-234	1.1E-05	4.8E-06	3.5E-06	CSA N288.1 (2014) Table C.1
U-235	1.0E-05	4.3E-06	3.1E-06	CSA N288.1 (2014) Table C.1
U-238	9.4E-06	4.0E-06	2.9E-06	CSA N288.1 (2014) Table C.1
Radionuclide	**Effective Dose Coefficients for External Soil Dose (in Sv/yr per Bq/m^2)**			
	Infant	**Child**	**Adult**	**Ref**
U-234	2.41E-11	1.85E-11	1.85E-11	CSA N288.1 (2014) Table C.4
U-235	6.38E-09	4.91E-09	4.91E-09	CSA N288.1 (2014) Table C.4 (+)
U-238	4.77E-09	3.67E-09	3.67E-09	CSA N288.1 (2014) Table C.4 (+)
Radionuclide	**Effective Dose Coefficients for Air Immersion Dose (in Sv/yr per Bq/m^3)**			
	Infant	**Child**	**Adult**	**Ref**
U-234	2.51E-10	1.93E-10	1.93E-10	CSA N288.1 (2014) Table C.3
U-235	2.65E-07	2.04E-07	2.04E-07	CSA N288.1 (2014) Table C.3
U-238	1.03E-10	7.89E-11	7.89E-11	CSA N288.1 (2014) Table C.3
Radionuclide	**Effective Dose Coefficients for Water Immersion Dose (in Sv/yr per Bq/m^3)**			
	Infant	**Child**	**Adult**	**Ref**
U-234	5.71E-13	4.39E-13	4.39E-13	CSA N288.1 (2014), Table C.5
U-235	5.86E-10	4.51E-10	4.51E-10	CSA N288.1 (2014), Table C.5
U-238	3.27E-12	2.52E-12	2.52E-12	CSA N288.1 (2014), Table C.5

5.2.5 Non-Radiological Dose Calculation Methods

5.2.5.1 Incidental Ingestion of Soil

The non-radiological dose from incidental ingestion of soil is calculated for each COPC following Equation 5-7, based on CSA (2012):

$$D_s = \frac{C_s \times IR_s \times AF_{GIT} \times D_1 \times D_2 \times D_3}{BW \times LE} \quad (5\text{-}7)$$

Where:

D_s = dose from incidental ingestion of soil [mg/kg/d]

C_s = concentration of COPC in soil [mg/kg]

IR_s = incidental soil ingestion rate [kg/d]

AF_{GIT} = absorption factor for gastrointestinal tract (assumed equal to 1) [unitless]

D_1 = days per week exposed, divided by 7 days [d/d]

D_2 = weeks per year exposed, divided by 52 weeks [wk/wk]

D_3 = total years exposed to site (for carcinogens only) [yr]

BW = receptor body weight [kg]

LE = Life expectancy (for carcinogens only) [yr]

As shown in Table 5.5, an averaging time of 1 is used for assessing chronic exposure, whereas an averaging time of 0.5 is used for assessing short-term exposure (along with the appropriate short-term TRVs). In present calculations chronic exposure is assessed, and therefore the averaging time fraction is excluded.

5.2.5.2 Incidental Ingestion of Groundwater

The non-radiological dose from incidental ingestion of groundwater is calculated for each COPC, following Equation 5-8 (CSA 2012):

$$D_s = \frac{C_{gw} \times IR_{gw} \times AF_{GIT} \times D_1 \times D_2 \times D_3}{BW \times LE} \quad (5\text{-}8)$$

Where:

D_{gw} = dose from incidental ingestion of groundwater [mg/kg/d]

C_{gw} = concentration of COPC in groundwater [mg/L]

IR_{gw} = incidental groundwater ingestion rate [L/d]

AF_{GIT} = absorption factor for gastrointestinal tract (assumed equal to 1) [unitless]

D_1 = days per week exposed, divided by 7 days [d/d]

D_2 = weeks per year exposed, divided by 52 weeks [wk/wk]

D_3 = total years exposed to site (for carcinogens only) [yr]

BW = receptor body weight [kg]

LE = Life expectancy (for carcinogens only) [yr]

5.2.5.3 Ingestion of Contaminated Food

The non-radiological dose from ingestion of contaminated food is calculated for each COPC, following Equation 5-9 (CSA 2012):

$$D_{f\_ing} = \frac{[\sum(C_{food\_i} \times IR_{food\_i} \times RAF_{GIT} \times D_1)] \times D_2}{BW \times LE \times 365} \quad (5\text{-}9)$$

Where:

D_{f_ing} = dose from contaminated food ingestion [mg/kg/d]

C_{food_i} = concentration of COPC in food item "i" [mg/kg]

IR_{food_i} = ingestion rate of food item "i" [kg/d]

RAF_{GIT} = relative absorption factor for the gastrointestinal tract, for a particular COPC, in food item "i" (assumed equal to 1) [unitless]

D_1 = days per year over which the consumption of food "i" occurs [d/yr]

D_2 = total years exposed to site (for carcinogens only) [yr]

BW = receptor body weight [kg]

LE = Life expectancy (for carcinogens only) [yr]

365 = total days per year (constant) [d/yr]

For the purposes of this study, consumption of contaminated foods is assumed to occur 365 days per year (D1). Therefore, mathematically D1 (numerator) and 365 (denominator) in the equation above can be omitted.

5.2.5.4 Incidental Ingestion of Surface Water While Swimming

The non-radiological dose from incidental ingestion of surface water while swimming (or falling into the harbour) is calculated for each COPC, following Equation 5-10 (CSA 2012):

$$D_{sw} = \frac{C_{sw} \times IR_{sw} \times ET \times EF \times ED}{BW \times AT} \quad (5\text{-}10)$$

Where:

D_{sw}	=	dose from incidental ingestion of surface water while swimming or falling into the harbour [mg/kg/d]
C_{sw}	=	concentration of COPC in surface water [mg/L]
IR_{sw}	=	incidental surface water ingestion rate [L/hr]
ET	=	exposure time [hours/event]
EF	=	exposure frequency [events/yr]
ED	=	exposure duration [yrs]
BW	=	receptor body weight [kg]
AT	=	averaging time (i.e., period over which the exposure is averaged) [d]

5.2.5.5 Soil Dermal Uptake

The non-radiological dose from dermal soil uptake is calculated for each COPC, following Equation 5-11. Equation 5-11 is based on the calculation methods of Health Canada (2010) and US EPA (2004b), with terms included for averaging time (for carcinogenic COPC calculations), consistent with CSA (2012):

$$D^{s}_{dermal} = \frac{C_s \times SA \times SL \times RAF \times EF_s \times D_2/7 \times D_3/52 \times D_4 \times CF}{BW \times AT} \quad (5\text{-}11)$$

Where:

D^{s}_{dermal}	=	exposure to COC in soil through the dermal pathway [mg/(kg-d)]
C_s	=	soil concentration [mg/kg]
SA	=	exposed skin surface area [cm^2]
SL	=	soil loading to exposed skin [(mg)/(cm^2 event)]
RAF	=	dermal absorption factor [-]
EFs	=	exposure frequency to soil [events/d]
$D_2/7$	=	days per week exposed/7 days [d/d]
$D_3/52$	=	weeks per year exposed/52 weeks [wk/wk]
D_4	=	total years exposed to site (for carcinogenic COC only) [yr]

BW = receptor body weight [kg]

AT = averaging time (for carcinogenic COC only) [yr]

CF = conversion factor 1.0×10^{-6} [kg/mg]

The value for the soil loading to exposed skin is based on the soil adherence value, which represents the amount of soil retained on the skin, and the skin surface area. Several studies have attempted to determine the soil adherence value and are summarized in U.S. EPA (2004b). Health Canada (2010b) provides separate adherence factors for hands and other surfaces which are summed to provide a total exposed skin surface area.

Table 5.13 summarizes the dermal absorption fractions used in the calculations of dermal exposure to soil. Values were obtained according to the following hierarchy:

1. Health Canada (2010b);
2. MOE (2011b);
3. US EPA (2004b);
4. Default value of 10% (Health Canada, 2010b).

Table 5.13 HHRA – Dermal Absorption Factors

COPC	Dermal Absorption Factors [unitless] [a]
Uranium	0.1
PCE	0.03
TCE	0.03
1,1-DCE	0.03
Cis-1,2-DCE	0.03[b]
Trans-1,2-DCE	0.03[b]
TCA	0.03[c]
Chloroethane	0.03[c]
VC	0.03

Note:
[a] Health Canada (2010b); Table 3
[b] MOE (2011b)
[c] Health Canada (2010b); default value for VOCs.

5.2.5.6 Surface Water & Groundwater Dermal Uptake

The non-radiological dose from dermal uptake of water (groundwater or surface water) is calculated for each COPC, following the general Equation 5-12 (based on US EPA 2004b, consistent with CSA 2012). However, this calculation varies depending on the COPC by way of the absorbed dose term (i.e., DA_{ev} in the Equation 5-12 below), which is calculated using different methods for inorganic COPCs versus organic COPCs:

$$D_{dermal}^{w} = \frac{DA_{ev} \times SA \times EF_{w} \times D_2/7 \times D_3/52 \times D_4}{BW \times AT} \quad (5\text{-}12)$$

Where:

D_{dermal}^{w}	=	exposure to COC in water through the dermal pathway [mg/(kg-d)]
DA_{ev}	=	absorbed dose per event [mg/cm^2/event]
SA	=	exposed skin surface area [cm^2]
EF_w	=	exposure frequency to water [events/d] {assumed to be 1 event per day}
$D_2/7$	=	days per week exposed/7 days [d/d]
$D_3/52$	=	weeks per year exposed/52 weeks [wk/wk]
D_4	=	total years exposed to site (for carcinogenic COC only) [yr]
BW	=	body weight [kg]
AT	=	averaging time (for carcinogenic COCs only) [yr]

Inorganic COPCS - DA_{ev}

For inorganic COPCs, the skin has a limited capacity to reduce the transport rate and the viable epidermis does not act as a barrier. Therefore, the absorbed dose (DA_{ev}) can be calculated from Equation 5-13:

$$DA_{ev} = \frac{K_p \times C_w \times t_{ev}}{CF} \quad (5\text{-}13)$$

Where:

DA_{ev}	=	absorbed dose per event [mg/cm^2/ev]
K_p	=	dermal permeability coefficient in water [cm/h]
C_w	=	concentration in water [µg/L]
t_{ev}	=	event duration [h/ev]
CF	=	conversion factor 1x10^{-6} [conversion from µg/L to mg/cm^3]

In this study, the exposure times used in dermal uptake equations are those presented in Table 5.5 and Table 5.6.

Organic COPCS - DA_{ev}

For organic COPCs, the calculation is dependent on the contact time and the time required to reach steady state. Equations 5-14 and 5-15 are used to estimate the absorbed dose (DA_{ev}):

If $t_{ev} \leq t^*$

$$DA_{ev} = 2 \times FA \times K_p \times \frac{C_w}{CF} \sqrt{6 \tau \frac{t_{ev}}{\pi}} \quad (5\text{-}14)$$

If $t_{ev} > t^*$

$$DA_{ev} = FA \times K_p \times \frac{C_w}{CF} \left[\frac{t_{ev}}{1+B} + 2\tau \left(\frac{1+3B+3B^2}{(1+B)^2} \right) \right] \quad (5\text{-}15)$$

Where:

FA	=	fraction absorbed [-]
τ	=	lag time [h]
t_{ev}	=	event time (duration) [h]
t^*	=	time to reach steady state [h]
CF	=	conversion factor $1x10^{-6}$ [$(mg/cm^3)/(\mu g/L)$]
B	=	ratio of the permeability coefficient of a compound through the stratum corneum relative to its permeability coefficient across the viable epidermis

In this study, the exposure times used in dermal uptake equations are those presented in Table 5.5 and Table 5.6.

For highly lipophilic chemicals or for chemicals that have a long lag time, some of the chemical dissolved into skin may be lost due to desquamation during that absorption period. The fraction absorbed (FA) term has been included to account for this loss of chemical due to desquamation. The conservative default for this parameter is 1 (i.e., assuming no loss due to desquamation), which is used in this assessment. However, alternative values can be obtained on a chemical-specific basis from U.S. EPA (2004b).

An empirical predictive correlation is provided to estimate the permeability coefficient for organics:

$$\log K_p = -2.80 + 0.66 \log K_{ow} - 0.0056 MW \quad (5\text{-}16)$$

Where:

K_{ow} = octanol-water partition coefficient

MW = molecular weight [g/mole]

Chemicals with very large and very small K_{ow} values are outside of the range of the empirical relationship; however, the relationship can be used as a preliminary estimate (U.S. EPA 2004b).

Assuming that the thickness of the stratum corneum is 0.001 cm the following equation can be used to determine the lag time:

$$\tau = 0.105 \times 10^{(0.0056\,MW)} \quad (5\text{-}17)$$

For longer exposure durations, the absorbed dose is restricted by the permeability of the viable epidermis and the stratum corneum, and thus B, the ratio of the permeability of the stratum corneum to that of the epidermis is an important factor in the equation. The value of B can be approximated by:

$$B = K_p \frac{\sqrt{MW}}{2.6} \quad (5\text{-}18)$$

The calculation of the time to reach steady state (t*) is dependent on B according to the following equations:

If $B \leq 0.6$ $$t^* = 2.4\tau \quad (5\text{-}19)$$

If $B > 0.6$ $$t^* = 6\tau(b - \sqrt{b^2 - c^2}) \quad (5\text{-}20)$$

$$c = \frac{1 + 3B + 3B^2}{3(1 + B)} \quad (5\text{-}21)$$

$$b = \frac{2(1 + B)^2}{\pi} - c \quad (5\text{-}22)$$

Where:

b,c = correlation coefficients

Table 5.14 summarizes the dermal permeability coefficients (Kp values) used in the calculations of dermal exposure to surface water or groundwater.

Table 5.14 HHRA – Dermal Permeability Coefficients

(Groundwater & Surface Water)

COPC	Dermal Permeability Coefficient (K_p) (cm/h)	Notes & Reference
Uranium	0.001	Default value for inorganics (US EPA 2004b; Exhibit 3-1)
Chloroethane	0.0061	US EPA 2004b; App. B-2
1,1-DCE	0.012	US EPA 2004b; App. B-2
Cis-1,2-DCE	0.0077	US EPA 2004b; App. B-2 (value for trans-1,2-DCE)
Trans-1,2-DCE	0.0077	US EPA 2004b; App. B-2
PCE	0.033	US EPA 2004b; App. B-2
TCE	0.012	US EPA 2004b; App. B-2
VC	0.0056	US EPA 2004b; App. B-2
1,1,1-TCA	0.013	US EPA 2004b; App. B-2

5.2.5.7 Inhalation

In general, the non-radiological dose from inhalation (of outdoor air, or dust/particulate in air) is calculated for each COPC, following Equation 5-23, consistent with CSA (2012). Equation 5-23 calculates a dose in mg/kg-d that is compared to a slope factor or reference dose TRV (depending on carcinogenic effects for a particular COPC). However, for many chemical compounds, TRVs for the inhalation pathway are expressed as reference concentrations (in mg/m^3). In such cases, Equation 5-24 is used to calculate exposure:

$$D_{sp} = \frac{C_s \times P_{air} \times IR_a \times AF_{INH} \times D_1 \times D_2 \times D_3 \times D_4}{BW \times LE} \quad (5\text{-}23)$$

Where:

D_{sp} = dose from inhalation of soil dust/particulate [mg/kg/d]

C_s = concentration of COPC in soil [mg/kg]

P_{air} = particulate concentration in air [kg/m^3]

IR_a = receptor air inhalation rate [m^3/d]

AF_{NH} = absorption factor for inhalation (assumed equal to 1) [unitless]

D_1 = hours per day exposed, divided by 24 hours [hr/hr]

D_2 = days per week exposed, divided by 7 days [d/d]

D_3 = weeks per year exposed, divided by 52 weeks [wk/wk]

D_4 = total years exposed to site (for carcinogens only) [yr]

BW = receptor body weight [kg]

LE = Life expectancy (for carcinogens only) [yr]

$$D_{sp} = \frac{C_s \times P_{air} \times D_1 \times D_2 \times D_3 \times D_4}{LE} \quad (5\text{-}24)$$

Where:

D_i = exposure from inhalation [mg/m^3]

C_s = concentration of COPC in soil [mg/kg]

P_{air} = particulate concentration in air [kg/m^3]

D_1 = hours per exposure event, divided by 24 hours [hr/hr]

D_2 = days per week exposed, divided by 7 days [d/d]

D_3 = weeks per year exposed, divided by 52 weeks [wk/wk]

D_4 = total years exposed to site (for carcinogens only) [yr]

LE = Life expectancy (for carcinogens only) [yr]

In the absence of measured air concentrations, concentrations of COCs associated with particulate in ambient air can be estimated from soil data using an assumed respirable (≤ 10 µm aerodynamic diameter) particulate concentration. For the maintenance and sub-surface workers who may be exposed to a higher concentration of particulates as a result of soil resuspension during typical activities, a respirable particulate concentration of 60 µg/m^3 (or 6.0x10^{-8} kg/m^3) is typically used (MOE 2011b). For all resident receptors, a value of 0.76 µg/m^3 (or 7.6x10^{-10} kg/m^3) as provided by Health Canada (2010a) is typically used for areas with no construction activities.

In this study, both measured and derived air concentrations are used, depending on the data available for a particular exposure location. Therefore, when measured data are available, the air inhalation calculation replaces C_s (mg/kg) and P_{air} (kg/m^3) in Equation 5-24 with the modeled air concentration (in µg/m^3), with the appropriate unit conversion.

5.2.6 Transfer Factors - HHRA

Transfer factors are needed in order to estimate the concentration of radionuclides and COPCs in foods consumed by human receptors, namely fish consumption. Overall, the selection of transfer factors follows the CSA N288.6 (2012) recommended hierarchy sources, and obtains transfer factors for HHRA from CSA N288.1 (2014) as shown in Table 5.15.

Table 5.15 HHRA: Transfer Factors (Bioaccumulation Factors)

Factor	U	Reference	Notes
Fish-Water TF (L/kg FW)	0.96	CSA N288.1 (2014); Table A.25a *(Bioaccumulation Factor; transfer from freshwater to freshwater fish muscle.)*	Applicable to U-238, U-234, and U-235
Plant-Soil TF (kg/kg DW)	0.01	CSA N288.1 (2014); Table G.3 *(Concentration Ratio; transfer from soil to terrestrial plants.)*	Applicable to U-238, U-234, and U-235
Plant-Air TF (m^3/kg FW)	4890	CSA N288.1 (2014) Table A.5a (Site-specific default values of P_{14}, transfer from air to plant for the Darlington site; generic fruits and vegetables)	Applicable to U-238, U-234, and U-235

5.2.7 Gamma Dose Rates

Gamma dose rates are estimated based on measured gamma levels at fenceline monitoring stations (see Figure 2.10 and at in-plant monitoring stations. Gamma dose rates are estimated for each receptor based on their location, and are then added to each receptor's total radiation dose from radionuclides (as shown in Section 5.4.3.1).

Fenceline gamma measurement data from 2014 is presented in Table 5.16 below.

Table 5.16 Gamma Fenceline Monitoring Data from 2014 (µSv/hr) [Cameco 2015a]

Fenceline Location	Reg. Limit (DRL)	Action Level	Annual Average	Quarterly Max.
1	0.35	0.2	0.01	0.02
2	1.18	1	0.03	0.03
3	1.18	1	0	0
4	1.18	1	0	0
5	1.18	1	0	0
6	1.18	1	0	0
7	1.18	1	0	0
8	1.18	1	0	0
9	1.18	1	0.06	0.07
10	1.18	1	0	0
11	1.18	1	0.43	0.44
12	**1.18**	**1**	**0.93**	**0.97**

In-plant gamma measurement data from 2014 is presented in Table 5.17 below.

Table 5.17 Quarterly In-Plant Gamma Monitoring Data from 2014 (µSv/hr) [Cameco 2015a]

Location #	Area	Average	Minimum	Maximum
13	[redacted]	0.1	0.1	0.2
14		1.7	1.4	2.1
15		1.9	1.6	2.1
16		1.2	1.1	1.3
17		0.4	0.4	0.5
18		2.3	2.2	2.4
19		2.1	1.8	2.4
20		1.2	1	1.3
21		0.2	0.1	0.2
22		0.9	0.7	1.1
23		1.5	1.2	1.8
24		0.2	0.1	0.2
25		0.3	0.2	0.3
26		0.7	0.6	0.8
27		0.7	0.6	0.8
28		0.1	0.1	0.2
29		2	0.4	5.6
30		4.3	3.7	5.2
31		1.8	1.3	2.3
32		2.4	2.2	2.7
33		0.7	0	1
34		1.3	1.1	1.6
35		5.4	4.2	7.6
36		1.3	0.9	1.5
37		0.1	0	0.2
38		12.9	10.4	16.3
39		3.2	2.7	3.6
40		0.1	0	0.1
41		0.2	0.1	0.4
42		0.1	0.1	0.2
43		0	0	0.1
44		0	0	0
45		0	0	0.1
46		0.1	0	0.2
47		0	0	0.1
48		0.1	0	0.3
49		0.1	0	0.2
50		1.1	0.7	1.5
51		0.1	0	0.1
52		0.3	0.1	0.6
53		0.2	0.2	0.3
54	*Omitted: see Cameco 2015a*			
55	[redacted]	0.2	0.1	0.5
56		2	0.8	3.3
	max	12.90	-	16.30
	average	1.29	-	1.70
	95th percentile	4.19	-	5.56

Gamma dose rates for on-site receptors are based on the 95th percentile of maximum quarterly in-plant *ambient* gamma measurements, as shown in Table 5.18. However, it is not appropriate to use ambient gamma levels directly for effective dose rate estimation; so, effective gamma dose rate calculations are provided in Appendix D.

Table 5.18 Ambient Gamma Dose Rates Associated with On-Site Receptors

Receptor	Receptor Location	Associated In-Plant Gamma Station	Associated *Ambient* Gamma Dose Rate (µSv/hr)
Onsite Subsurface Worker	Various; Indoors & outdoors	95th percentile among all in-plant data	5.56
Onsite Maintenance Worker	Various; indoors	95th percentile among all in-plant data	5.56

Gamma dose rates for off-site receptors are calculated based on ambient fenceline gamma measurements, though the exact ambient gamma dose rate used varies depending on the receptor's location. Table 5.19 identifies the *ambient outdoor* gamma dose rate used for each receptor based on their location. Again, it is not appropriate to use ambient gamma levels directly for effective dose rate estimation; so, effective gamma dose rate calculations are provided in Appendix D.

Table 5.19 Ambient Gamma Dose Rates Associated with Off-site Receptors

Receptor	Receptor Location	Associated Fenceline Gamma Station	Associated *Ambient* Gamma Dose Rate (µSv/hr)
Offsite Commercial Worker	East and South of facility	TLD 3-7 (See Figure 2.10)	0 (See Table 5.17)
Offsite Maintenance Worker			
Offsite Subsurface Worker	Various outdoors, beyond facility fenceline	Maximum among fenceline gamma readings	0.97
Offsite Resident Worker	North and west of facility	Maximum quarterly reading among TLD 1,2 and 12 (See Figure 2.10)	0.97

5.3 Toxicity Assessment

5.3.1 Non-Radiological COPCs - Toxicological Reference Values

Exposure to non-radionuclide contaminants (i.e. chemical contaminants) is conventionally assessed against Toxicity Reference Values (TRVs). Toxicity is the potential of a chemical to cause some type of damage, either permanent or temporary, to the structure or functioning of any part of the body. The toxicity depends on the amount of the chemical taken into the body (generally termed the intake or dose) and the length of time a person is exposed. Every chemical has a specific dose and duration of exposure that is necessary to produce a toxic effect in humans. Toxicity assessments generally involve the evaluation of scientific studies, based either on laboratory animal tests or on workplace exposure investigations, by a number of experienced scientists in a wide range of scientific disciplines in order to determine the maximum dose that a human can be exposed to without having an adverse health effect.

Toxicity assessments generally categorize adverse effects as short term (acute) or long term (chronic). This HHRA focuses on the assessment of long term (chronic) effects.

Carcinogenic TRVs

Carcinogenesis is generally assumed to be a "non-threshold" type phenomenon whereby it is assumed that any level of exposure to a carcinogen poses a finite probability of generating a carcinogenic response. Carcinogenic TRVs or slope factors are used to estimate an upper-bound lifetime probability of an individual developing cancer as a result of exposure to a particular level of a potential carcinogen. The carcinogenic TRV is, therefore, the incremental lifetime cancer risk per unit of dose.

Non Carcinogenic TRVs

For many non-carcinogenic effects, protective biological mechanisms must be overcome before an adverse effect from exposure to the chemical is manifested. For this reason, scientists generally agree that there is a level (threshold) below which no adverse effects would be measurable or expected to occur. This is known as a "threshold" concept. Non-carcinogens are often referred to as "systemic toxicants" because of their effects on the function of various organ systems. These toxicity reference values are generally called reference doses (RfDs), tolerable daily intakes (TDIs) or acceptable daily intakes (ADIs) and are generally derived by regulatory agencies such as Health Canada and the United States Environmental Protection Agency (U.S. EPA). These TRVs are usually expressed as the quantity of a chemical per unit body weight per unit time (mg/kg-day) or as an air concentration (mg/m^3) and have generally been derived for sensitive individuals in the public using the most sensitive endpoint available. These factors involve the incorporation of “uncertainty factors” by regulatory agencies to provide protection for members of the public.

There are several sources that report TRVs for evaluation of effects from long-term (i.e., chronic) exposure. The SENES & EcoMetrix (2012) report entitled *Compilation and Critical Review of Toxicity Reference Values for Use in Risk Assessments for Cameco Facilities in Canada* consolidates and critically reviews TRVs for

several key chemical compounds, and provides final recommended TRV values. The SENES & EcoMetrix (2012) study encompasses TRV data from a wide range of sources recommended by CSA (2012), including:

- Health Canada;
- US California EPA (CalEPA);
- U.S. EPA Integrated Risk Information System (IRIS) database;
- World Health Organization (WHO); and
- Agency for Toxic Substances and Disease Registry (ATSDR).

As such, SENES & EcoMetrix (2012) represents some of the most recent and comprehensive TRV information for Cameco sites available at this time, and is used preferentially as the source for human-health TRV data. SENES & EcoMetrix (2012) contains detailed discussions of the nature of adverse effects, available data, study methods, uncertainties, and TRV selection process for individual chemicals. The reader is referred to the SENES & EcoMetrix (2012) study for this information.

If TRV information could not be found in SENES & EcoMetrix (2012), then additional sources were used, according to CSA N288.6 (2012) recommendations. These include:

1. Health Canada;
2. Ontario Ministry of Environment (MOE) – *citing CalEPA, IRIS, RIVM and others*;
3. Canadian Council of Ministers of the Environment (CCME);
4. US California EPA (CalEPA);
5. U.S. EPA Integrated Risk Information System (IRIS) database;
6. World Health Organization (WHO);
7. Netherlands National Institute of Public Health and the Environment (RIVM); and
8. Agency for Toxic Substances and Disease Registry (ATSDR).

If TRV information could not be found from the CSA N288.6 (2012) hierarchy of sources, then additional references were reviewed. Table 5.20 presents the human-health TRVs selected for use in this assessment.

Table 5.20 HHRA – TRVs

COPC	Pathway of Exposure*	Carc. vs. Non-Carc.**	Value	Units	Health Effect	Ref
Uranium	Oral	non-carc.	6×10^{-4}	mg/(kg-d)	Degenerative lesions in kidney tubules	SENES & EcoMetrix 2012: *Health Canada 2010b* *Based on ingestion exposure to soluble uranium (uranyl nitrate hexahydrate).*
	Inhalation	non-carc.	4.0×10^{-5}	mg/m^3	Kidney effects	ATSDR 2013 *(more recent than the ATSDR 1999 reference in MOE 2011b).*
Chloroethane (CA; 'Ethyl Chloride')	Oral		-	-	-	
	Inhalation	Non-carc.	1.0×10^{1}	mg/m^3	Delayed fetal ossification	IRIS 1991
1,1-Dichloroethylene (1,1-DCE)	Oral	Non-carc	4.0×10^{-2}	mg/kg-d	Liver toxicity	MOE 2011b: *IRIS 2002*
	Inhalation	Non-carc	7.0×10^{-2}	mg/m^3		MOE 2011b: *CalEPA 2000*
cis-1,2-Dichloroethylene (cis-1,2-DCE)	Oral	Non-carc	2.0×10^{-3}	mg/kg-d	Kidney effects – increased kidney relative weight.	IRIS 2010 *(more recent than referenced in MOE 2011b)*
	Inhalation	Non-carc	1.5×10^{-1}	mg/m^3	-	MOE 2011b: *RIVM 2001*
trans-1,2-Dichloroethylene (trans-1,2-DCE)	Oral	Non-carc	2.0×10^{-2}	mg/kg-d	Increased relative liver weights. Immunological effects: decreased thymus weights; decreased anti-body forming spleen cell counts Decreased kidney weights.	IRIS 2010 *(more recent than referenced in MOE 2011b)*
	Inhalation	Non-carc	6.0×10^{-2}	mg/m^3	Liver effects: degeneration of liver lobules and Kupfer cells. Lung effects: hypaemia, alveolar degeneration.	MOE 2011b: *RIVM 2001*
Tetrachloroethylene (PCE)	Oral	Non-carc	6.0×10^{-3}	mg/kg-d		

COPC	Pathway of Exposure*	Carc. vs. Non-Carc.**	Value	Units	Health Effect	Ref
	Inhalation	Non-carc	$4.0x10^{-3}$	mg/m^3	Neurotoxicity: cognitive effects, vision, reaction time.	IRIS 2012 *(more recent than referenced in MOE 2011b)*
	Oral	Carc.	$2.1x10^{-3}$	$(mg/kg\text{-}d)^{-1}$	Hepatocellular carcinomas and adenomas.	
	Inhalation	Carc.	$2.6x10^{-4}$	$(mg/m^3)^{-1}$		
1,1,1-Trichloroethane (TCA)	Oral	Non-carc	$2.0x10^{0}$	mg/kg-d	Reduced body weight	MOE 2011b: *IRIS 2007*
	Inhalation	Non-carc	$1.0x10^{0}$	mg/m^3	Liver histopathological effects; neurological effects.	MOE 2011b: *CalEPA 2000*
Trichloroethylene (TCE)	Oral	Non-carc	$5.0x10^{-4}$	mg/kg-d	Immunological effects: decreased thymus weight; decreased plaque-forming cell response. Cardiac malformations.	IRIS 2011 *(more recent than referenced in MOE 2011b)*
	Inhalation	Non-carc	$2.0x10^{-3}$	mg/m^3		
	Oral	Carc.	$4.6x10^{-2}$	$(mg/kg\text{-}d)^{-1}$	Primarily kidney cell tumors; also non-Hodgkins lymphoma and liver tumor formation.	
	Inhalation	Carc.	$4.8x10^{-3}$	$(mg/m^3)^{-1}$		IRIS 2011 *(more recent than referenced in MOE 2011b)* full lifetime value
Vinyl Chloride (VC)	Oral	Non-carc	$3.0x10^{-3}$	mg/kg-d	Liver effects: cell polymorphism	MOE 2011b: *ASTDR 2006; IRIS 2000*
	Inhalation	Non-carc	$1.0x10^{-1}$	mg/m^3		MOE 2011b: *IRIS 2000*
	Oral	Carc.	$1.4x10^{0}$	$(mg/kg\text{-}d)^{-1}$	Liver tumors: carcinomas, angiosarcomas, neoplastic nodules.	
	Inhalation	Carc.	$8.8x10^{-3}$	$(mg/m^3)^{-1}$		

5.3.2 Radiological Dose Limits

The radiological benchmarks used in this HHRA are based on the dose limits in the Nuclear Safety and Control Act Radiation Protection Regulations (CNSC 2000, see Table 5.21). These benchmarks were compared to the estimated doses in order to characterize risk.

Table 5.21 HHRA – Radiological Benchmarks

Receptor	Dose Limit	Reference
Member of the public	1 mSv/y	CNSC (2000) - *Nuclear Safety and Control Act*, Radiation Protection Regulations
Non-NEWs, including maintenance workers and technicians	1 mSv/y	CNSC (2000) - *Nuclear Safety and Control Act*, Radiation Protection Regulations
NEWs, including short-term contractors	20 mSv/y (i.e., 100 mSv over 5y)	CNSC (2000) - *Nuclear Safety and Control Act*, Radiation Protection Regulations

Note:
NEW – Nuclear Energy Worker

5.4 Risk Characterization

Risk characterization involves the integration of the information from the exposure assessment and the toxicity assessment.

5.4.1 Radiological Risk Characterization

Radiological risk characterization involves comparing the total estimated annual dose to the dose limits outlined in Section 5.3.2. To facilitate identification of doses that exceed the dose limit, a screening index (SI) is calculated by dividing the estimated dose by the dose limit; in this way any resulting SI values greater than one represent a dose estimate that exceeds the dose limit.

5.4.2 Non-Radiological Risk Characterization

For this study, both non-carcinogens and carcinogens are included.

For many non-carcinogenic effects, protective biological mechanisms must be overcome before an adverse effect is manifested from exposure to the COC. This is known as a "threshold" concept. For non-carcinogenic COCs, the hazard quotient (HQ) is used to assess the potential for effects. Consistent with CSA (2012), HQs are calculated for threshold-acting chemicals on a *per medium basis*. It is important to note that TRVs specific to the dermal absorption pathway are largely not available. As such, oral toxicity data have been used as surrogates for the dermal pathway. Therefore it is appropriate to combine the oral and dermal exposures together (summed). In general, inhalation HQs are provided separately since effects resulting from inhalation exposure are generally for a different endpoint compared to the oral route. The inhalation HQs are summed

with those from the oral and dermal pathways only if the endpoints for the different routes of exposure are the same. Overall, Equation 5-27 defines the HQ calculation procedure:

(5-27)

$$HQ_{ODs} = \frac{D_{INGs}}{TRV_o} + \frac{D_{DERMALs}}{TRV_d}$$

$$HQ_{ODgw} = \frac{D_{INGgw}}{TRV_o} + \frac{D_{DERMALgw}}{TRV_d}$$

$$HQ_i = \frac{D_{a,p} + D_{a,v}}{TRV_i}$$

Where:

HQ_{ODs}	=	HQ for oral ingestion (soil), including dermal contribution
HQ_{ODgw}	=	HQ for oral ingestion (groundwater), including dermal contribution
D_{INGs}	=	Dose from incidental soil ingestion
D_{INGgw}	=	Dose from incidental groundwater ingestion
$D_{DERMALs}$	=	Dose from dermal exposure to soil
$D_{DERMALgw}$	=	Dose from dermal exposure to groundwater
HQ_o	=	Hazard quotient – oral exposure [-]
HQ_i	=	Hazard quotient – inhalation exposure [-]
$D_{a,p}$	=	Dose from airborne soil particulate
$D_{a,v}$	=	Dose from airborne soil vapours
TRV_i	=	Toxicity Reference Value for inhalation exposure (RfC) [mg/m^3]
TRV_o	=	Toxicity Reference Value for oral exposure (RfD) [mg/(kg-d)]
TRV_d	=	Toxicity Reference Value for dermal exposure [mg/(kg-d)] *(TRV_d assumed equal to TRV_o)*

When all pathways of exposure and background sources are considered, if the HQ is below a value of 1.0, no potential exists for an adverse effect for the selected receptor. However, in this assessment there are potential pathways of exposure from other sources that have not been included (e.g., natural background levels in water, store-bought food, etc.). For this reason, the calculated HQ is compared to a more conservative value of 0.2, consistent with risk assessment practice (CSA 2012).

For carcinogenic COCs, an incremental lifetime cancer risk (ILCR) is calculated by multiplying the estimated dose (in mg/(kg-d)) by the appropriate slope factor (in (mg/(kg-d))$^{-1}$) for dermal and oral exposures, and the amortized air concentration (mg/m^3) by the appropriate unit risk (in (mg/m^3)$^{-1}$) for inhalation. This is shown in Equation (5-28). The estimate corresponds to an incremental risk of an individual developing cancer over a lifetime as a result of exposure. Risk is defined as follows:

$$Risk_o = \left(D_s \times TRV_o\right) + \left(D^s_{dermal} \times TRV_d\right) \quad (5\text{-}28)$$

$$Risk_i = \left(D_{a,p} + D_{a,v}\right) \times TRV_i$$

Where:

TRV_o	=	TRV for carcinogenic effects from oral exposure (SF) [$(mg/(kg\text{-}d))^{-1}$]
TRV_d	=	TRV for carcinogenic effects from dermal exposure [$(mg/(kg\text{-}d))^{-1}$] (assumed equal to TRV_o)
TRV_i	=	TRV for carcinogenic effects from inhalation (UR) [$(mg/m^3)^{-1}$]

The intakes of COPCs for the different pathways of exposure are estimated as outlined in Section 5.2.5, and the TRVs used in this HHRA are presented in Section 5.3.1. The calculated risk is then compared to acceptable benchmarks. In this assessment, an incremental risk level of 1×10^{-6} (1 in 1,000,000) was used to assess carcinogenic effects, consistent with the MOE (2011b) to represent an "essentially negligible" risk.

5.4.2.1 Addition Across Exposure Routes

Combining Oral and Dermal Exposures:

In an HHRA, it is generally acceptable to sum hazard quotients or risk levels across exposure routes when the adverse health effect has the same toxicological endpoint and mechanism of action.

In this assessment, it was considered that the mechanisms of action for the oral and dermal exposure routes (when toxicity values are available) are the same for all contaminants, and therefore HQs and risks were summed across the oral and dermal exposure routes.

Combining Oral, Dermal, and Inhalation Exposures:

Inhalation was also added to the oral and dermal total only if the endpoint and mechanism of action were the same as those for oral and dermal exposure. The inhalation TRVs outlined in Table 5.20 were reviewed for common endpoints and mechanisms of action. Of the identified COPCs for this HHRA, the following were found to have common endpoints and therefore their inhalation components can be combined with their dermal and oral components:

- Non-Carcinogenic Exposure: Uranium, 1,1-DCE; PCE; VC
- Carcinogenic Exposure: PCE; TCE; VC.

5.4.3 Risk Estimation

5.4.3.1 Radiological Risk

The following tables present the estimated radiological doses for worker and member of public receptors, based on their respective environmental media and exposure locations, along with a comparison to the dose limit outlined in Section 5.3.2).

Table 5.22 HHRA – T1 Radiological Results – All Receptors

(based on U-238, U-234, and U-235)

Receptor	Age Group	Estimated Annual Dose from Radionuclides (mSv/y)	Estimated Annual Gamma Dose (mSv/y)	Estimated Total Dose (mSv/y)	Annual Dose Limit (mSv/y)	SI
Onsite Maintenance Worker	Adult	0.11	0.31	0.42	1	0.42
Onsite Subsurface Worker	Adult	0.00012	0.31	0.31	1	0.31
Offsite Maintenance Worker	Adult	0.00020	0	0.00020	1	0.00020
Offsite Commercial Worker	Adult	0.000095	0	0.000095	1	0.000095
Offsite Subsurface Worker	Adult	0.0000043	0.027	0.027	1	0.027
Resident	Adult	0.0012	0.51	0.51	1	0.51
Resident	Child	0.0013	0.58	0.58	1	0.58
Resident	Infant	0.0011	0.66	0.66	1	0.66
Resident + Onsite Subsurface Worker	Adult	0.0013	0.82	0.82	1	0.82

5.4.3.2 Non-Radiological Hazard and Risk

The following tables present the estimated non-radiological hazard (non-carcinogenic) and risk (carcinogenic) results for worker and member of public receptors, based on their respective environmental media and exposure locations.

Tier 1 estimates are based on maximum concentrations in environmental media (i.e. groundwater, surface water, soil, and air) (see Section 5.2.2). Only those receptor-media combinations with estimated HQ or risk results that exceed their corresponding benchmark values are carried forward into Tier 2 calculations (discussed below).

Tier 2 estimates are performed only for those receptor-media combinations who's HQ or risk results exceeded their corresponding benchmark values in Tier 1. Tier 2 estimates are based on 95th percentile concentrations (see Section 5.2.2) in the appropriate environmental media (i.e. only those media that were identified via Tier 1 results).

Tier 1 – Non-Radiological:

Table 5.23 HHRA – T1 HQ & Risk – On-Site Maintenance Worker Receptor (Receptor #1)

a) Onsite Air (inhalation – indoor air)

NON-CARCINOGENIC EFFECTS	
COPC	HQi[a]
Uranium	**1.6**
1,1-Dichloroethylene	2.6E-05
cis-1,2-Dichloroethene	6.0E-05
trans-1,2-Dichloroethene	3.1E-05
Trichloroethylene	0.11
Vinyl chloride	8.9E-06
Chloroethane	NC
1,1,1-Trichloroethane (TCA)	NC
Tetrachloroethylene (PCE)	NC
CARCINOGENIC EFFECTS	
COPC	Riski[b]
Trichloroethylene	5.4E-07
Vinyl chloride	4.2E-09
Tetrachloroethylene (PCE)	NC

Shaded values indicate exceedance of corresponding HQ (0.2) or Risk ($1x10^{-6}$) benchmark value.
[a] HQi: Hazard Quotient for inhalation pathway
[b] Riski: Risk for inhalation pathway
N/C – Not Calculated: Key parameter inputs are unavailable (e.g. concentration, TRV, etc.)
N/A – Not Applicable (see Section 5.4.2.1)

b) Onsite Soil (Incidental ingestion, dust inhalation, dermal uptake)

NON-CARCINOGENIC EFFECTS			
COPC	HQi[a]	HQo+d[b]	HQt[c]
Uranium	2.4E-05	4.9E-03	5.2E-03
1,1-Dichloroethylene	1.6E-11	3.9E-09	3.9E-09
cis-1,2-Dichloroethene	7.3E-12	7.8E-08	NA
trans-1,2-Dichloroethene	1.8E-11	7.8E-09	NA
Trichloroethylene	8.2E-10	4.7E-07	NA
Vinyl chloride	1.4E-11	6.5E-08	6.5E-08
Chloroethane	2.7E-14	NC	NA
1,1,1-Trichloroethane (TCA)	1.4E-12	9.8E-11	NA
Tetrachloroethylene (PCE)	2.7E-10	2.6E-08	2.6E-08
CARCINOGENIC EFFECTS			
COPC	Riski[d]	Risko+d[e]	Riskt[f]
Trichloroethylene	4.2E-15	5.8E-12	5.8E-12
Vinyl Chloride	6.5E-15	1.5E-10	1.5E-10
Tetrachloroethylene (PCE)	1.5E-16	1.8E-13	1.8E-13

[a] HQi: Hazard Quotient for inhalation pathway
[b] HQo+d: Hazard Quotient for combined oral and dermal uptake pathways
[c] HQt: Hazard Quotient combined for all pathways (where applicable, see Section 5.4.2.1)
[d] Riski: Risk for inhalation pathway
[e] Risko+d: Risk for combined oral and dermal uptake pathways
[f] Riskt: Risk combined for all pathways (where applicable, see Section 5.4.2.1)
N/C – Not Calculated: Key parameter inputs are unavailable (e.g. concentration, TRV, etc.)
N/A – Not Applicable (see Section 5.4.2.1)

Table 5.24 HHRA – T1 HQ & Risk - On-Site Subsurface Worker Receptor (Receptor #2)

a) Onsite Air (inhalation – outdoor air)

NON-CARCINOGENIC EFFECTS	
COPC	HQi[a]
Uranium	2.79E-04
1,1-Dichloroethylene	N/A
cis-1,2-Dichloroethene	N/A
trans-1,2-Dichloroethene	N/A
Trichloroethylene	N/A
Vinyl chloride	N/A
Chloroethane	N/A
1,1,1-Trichloroethane (TCA)	N/A
Tetrachloroethylene (PCE)	N/A
CARCINOGENIC EFFECTS	
COPC	Riski[b]
Trichloroethylene	N/A
Vinyl chloride	N/A
Tetrachloroethylene (PCE)	N/A

[a] HQi: Hazard Quotient for inhalation pathway
[b] Riski: Risk for inhalation pathway
N/A – Not Applicable

b) Onsite Soil (Incidental ingestion, dust inhalation, soil vapour inhalation, dermal uptake)

NON-CARCINOGENIC EFFECTS			
COPC	HQi[a]	HQo+d[b]	HQt[c]
Uranium	2.4E-04	4.9E-03	5.2E-03
1,1-Dichloroethylene	1.0E-08	3.9E-09	1.4E-08
cis-1,2-Dichloroethene	1.1E-08	7.8E-08	N/A
trans-1,2-Dichloroethene	2.1E-08	7.8E-09	N/A
Trichloroethylene	1.0E-06	4.7E-07	N/A
Vinyl chloride	7.4E-09	6.5E-08	7.3E-08
Chloroethane	1.4E-11	NC	N/A
1,1,1-Trichloroethane (TCA)	1.3E-09	9.8E-11	N/A
Tetrachloroethylene (PCE)	3.4E-07	2.6E-08	3.7E-07
CARCINOGENIC EFFECTS			
COPC	Riski[d]	Risko+d[e]	Riskt[f]
Trichloroethylene	5.3E-12	5.8E-12	1.1E-11
Vinyl Chloride	3.5E-12	1.5E-10	1.5E-10
Tetrachloroethylene (PCE)	1.9E-13	1.8E-13	3.7E-13

[a] HQi: Hazard Quotient for inhalation pathway
[b] HQo+d: Hazard Quotient for combined oral and dermal uptake pathways
[c] HQt: Hazard Quotient combined for all pathways (where applicable, see Section 5.4.2.1)
[d] Riski: Risk for inhalation pathway
[e] Risko+d: Risk for combined oral and dermal uptake pathways
[f] Riskt: Risk combined for all pathways (where applicable, see Section 5.4.2.1)
N/C – Not Calculated: Key parameter inputs are unavailable (e.g. concentration, TRV, etc.)
N/A – Not Applicable (see Section 5.4.2.1)

c) Onsite Groundwater (Incidental ingestion, groundwater vapour inhalation, dermal uptake)

NON-CARCINOGENIC EFFECTS			
COPC	HQi[a]	HQo+d[b]	HQt[c]
Uranium	NE	1.2E-02	1.2E-02
1,1-Dichloroethylene	3.4E-05	1.6E-04	1.9E-04
cis-1,2-Dichloroethene	1.8E-05	2.0E-02	N/A
trans-1,2-Dichloroethene	1.5E-05	2.9E-04	N/A
Trichloroethylene	***9.6E-01***	***3.8E+01***	N/A
Vinyl chloride	8.5E-03	***2.7E-01***	***2.8E-01***
Chloroethane	8.2E-05	NC	N/A
1,1,1-Trichloroethane (TCA)	3.4E-04	1.0E-03	N/A
Tetrachloroethylene (PCE)	3.9E-04	4.7E-03	5.1E-03
CARCINOGENIC EFFECTS			
COPC	Riski[d]	Risko+d[e]	Riskt[f]
Trichloroethylene	***4.9E-06***	***9.0E-04***	***9.1E-04***
Vinyl Chloride	***4.0E-06***	***1.2E-03***	***1.2E-03***
Tetrachloroethylene (PCE)	2.2E-10	6.3E-08	6.3E-08

Shaded values indicate exceedance of corresponding HQ (0.2) or Risk ($1x10^{-6}$) benchmark value.
[a] HQi: Hazard Quotient for inhalation pathway
[b] HQo+d: Hazard Quotient for combined oral and dermal uptake pathways
[c] HQt: Hazard Quotient combined for all pathways (where applicable, see Section 5.4.2.1)
[d] Riski: Risk for inhalation pathway
[e] Risko+d: Risk for combined oral and dermal uptake pathways
[f] Riskt: Risk combined for all pathways (where applicable, see Section 5.4.2.1)
N/C – Not Calculated: Key parameter inputs are unavailable (e.g. concentration, TRV, etc.)
N/A – Not Applicable (see Section 5.4.2.1)

Table 5.25 HHRA – T1 HQ & Risk - Off-Site Commercial Worker Receptor (Receptor #3)

a) Offsite Air (inhalation – offsite indoor air)

NON-CARCINOGENIC EFFECTS	
COPC	**HQi[a]**
Uranium	3.5E-03
1,1-Dichloroethylene	6.5E-04
cis-1,2-Dichloroethene	3.1E-04
trans-1,2-Dichloroethene	7.6E-04
Trichloroethylene	3.7E-02
Vinyl chloride	1.2E-04
Chloroethane	NC
1,1,1-Trichloroethane (TCA)	NC
Tetrachloroethylene (PCE)	NC
CARCINOGENIC EFFECTS	
COPC	**Riski[b]**
Trichloroethylene	1.9E-07
Vinyl chloride	5.5E-08
Tetrachloroethylene (PCE)	NC

[a] HQi: Hazard Quotient for inhalation pathway
[b] Riski: Risk for inhalation pathway
N/C – Not Calculated: Key parameter inputs are unavailable (e.g. concentration, TRV, etc.)

Table 5.26 HHRA – T1 HQ & Risk – Off-Site Maintenance Worker Receptor (Receptor #4)

a) Offsite Air (inhalation – outdoor air)

NON-CARCINOGENIC EFFECTS	
COPC	**HQi[a]**
Uranium	7.0E-03
1,1-Dichloroethylene	N/A
cis-1,2-Dichloroethene	N/A
trans-1,2-Dichloroethene	N/A
Trichloroethylene	N/A
Vinyl chloride	N/A
Chloroethane	N/A
1,1,1-Trichloroethane (TCA)	N/A
Tetrachloroethylene (PCE)	N/A
CARCINOGENIC EFFECTS	
COPC	**Riski[b]**
Trichloroethylene	N/A
Vinyl chloride	N/A
Tetrachloroethylene (PCE)	N/A

[a] HQi: Hazard Quotient for inhalation pathway
[b] Riski: Risk for inhalation pathway
N/C – Not Applicable

b) Offsite Soil (Incidental ingestion, dust inhalation, dermal uptake)

NON-CARCINOGENIC EFFECTS			
COPC	HQi[a]	HQo+d[b]	HQt[c]
Uranium	1.7E-05	3.6E-04	3.7E-04
1,1-Dichloroethylene	N/A	N/A	N/A
cis-1,2-Dichloroethene	N/A	N/A	N/A
trans-1,2-Dichloroethene	N/A	N/A	N/A
Trichloroethylene	N/A	N/A	N/A
Vinyl chloride	N/A	N/A	N/A
Chloroethane	N/A	N/A	N/A
1,1,1-Trichloroethane (TCA)	N/A	N/A	N/A
Tetrachloroethylene (PCE)	N/A	N/A	N/A
CARCINOGENIC EFFECTS			
COPC	Riski[d]	Risko+d[e]	Riskt[f]
Trichloroethylene	N/A	N/A	N/A
Vinyl chloride	N/A	N/A	N/A
Tetrachloroethylene (PCE)	N/A	N/A	N/A

[a] HQi: Hazard Quotient for inhalation pathway
[b] HQo+d: Hazard Quotient for combined oral and dermal uptake pathways
[c] HQt: Hazard Quotient combined for all pathways (where applicable, see Section 5.4.2.1)
[d] Riski: Risk for inhalation pathway
[e] Risko+d: Risk for combined oral and dermal uptake pathways
[f] Riskt: Risk combined for all pathways (where applicable, see Section 5.4.2.1)
NA – Not Applicable – different endpoints (see Section 5.4.2.1).
N/A – Not Applicable – uranium is the only applicable COPC for this medium.

Table 5.27 HHRA – T1 HQ & Risk - Off-Site Subsurface Worker Receptor (Receptor #5)

a) Offsite Air (inhalation – outdoor air)

NON-CARCINOGENIC EFFECTS	
COPC	HQi[a]
Uranium	1.4E-04
1,1-Dichloroethylene	N/A
cis-1,2-Dichloroethene	N/A
trans-1,2-Dichloroethene	N/A
Trichloroethylene	N/A
Vinyl chloride	N/A
Chloroethane	N/A
1,1,1-Trichloroethane (TCA)	N/A
Tetrachloroethylene (PCE)	N/A
CARCINOGENIC EFFECTS	
COPC	Riski[b]
Trichloroethylene	N/A
Vinyl chloride	N/A
Tetrachloroethylene (PCE)	N/A

[a] HQi: Hazard Quotient for inhalation pathway
[b] Riski: Risk for inhalation pathway

N/C – Not Applicable

b) Offsite Soil (Incidental ingestion, dust inhalation, dermal uptake)

NON-CARCINOGENIC EFFECTS			
COPC	HQi[a]	HQo+d[b]	HQt[c]
Uranium	3.4E-07	7.1E-06	7.5E-06
1,1-Dichloroethylene	N/A	N/A	N/A
cis-1,2-Dichloroethene	N/A	N/A	N/A
trans-1,2-Dichloroethene	N/A	N/A	N/A
Trichloroethylene	N/A	N/A	N/A
Vinyl chloride	N/A	N/A	N/A
Chloroethane	N/A	N/A	N/A
1,1,1-Trichloroethane (TCA)	N/A	N/A	N/A
Tetrachloroethylene (PCE)	N/A	N/A	N/A
CARCINOGENIC EFFECTS			
COPC	Riski[d]	Risko+d[e]	Riskt[f]
Trichloroethylene	N/A	N/A	N/A
Vinyl chloride	N/A	N/A	N/A
Tetrachloroethylene (PCE)	N/A	N/A	N/A

[a] HQi: Hazard Quotient for inhalation pathway
[b] HQo+d: Hazard Quotient for combined oral and dermal uptake pathways
[c] HQt: Hazard Quotient combined for all pathways (where applicable, see Section 5.4.2.1)
[d] Riski: Risk for inhalation pathway
[e] Risko+d: Risk for combined oral and dermal uptake pathways
[f] Riskt: Risk combined for all pathways (where applicable, see Section 5.4.2.1)
NA – Not Applicable – different endpoints (see Section 5.4.2.1).
N/A – Not Applicable – uranium is the only applicable COPC for this medium.

c) Offsite Groundwater (Incidental ingestion, groundwater vapour inhalation, dermal uptake)

NON-CARCINOGENIC EFFECTS			
COPC	HQi[a]	HQo+d[b]	HQt[c]
Uranium	NE	5.0E-05	5.0E-05
1,1-Dichloroethylene	2.4E-07	1.1E-06	1.4E-06
cis-1,2-Dichloroethene	1.5E-06	1.7E-03	N/A
trans-1,2-Dichloroethene	1.2E-06	2.4E-05	N/A
Trichloroethylene	2.5E-03	9.9E-02	N/A
Vinyl chloride	5.0E-05	1.6E-03	1.7E-03
Chloroethane	2.0E-07	N/C	N/A
1,1,1-Trichloroethane (TCA)	1.0E-06	3.0E-06	N/A
Tetrachloroethylene (PCE)	8.2E-07	1.0E-05	1.1E-05
CARCINOGENIC EFFECTS			
COPC	Riski[d]	Risko+d[e]	Riskt[f]
Trichloroethylene	1.3E-08	***2.4E-06***	***2.4E-06***
Vinyl Chloride	2.4E-08	***7.0E-06***	***7.0E-06***
Tetrachloroethylene (PCE)	4.6E-13	3.1E-12	3.8E-12

Shaded values indicate exceedance of corresponding HQ (0.2) or Risk ($1x10^{-6}$) benchmark value.
[a] HQi: Hazard Quotient for inhalation pathway
[b] HQo+d: Hazard Quotient for combined oral and dermal uptake pathways
[c] HQt: Hazard Quotient combined for all pathways (where applicable, see Section 5.4.2.1)
[d] Riski: Risk for inhalation pathway
[e] Risko+d: Risk for combined oral and dermal uptake pathways
[f] Riskt: Risk combined for all pathways (where applicable, see Section 5.4.2.1)
N/C – Not Calculated: Key parameter inputs are unavailable (e.g. concentration, TRV, etc.)
N/A – Not Applicable (see Section 5.4.2.1)

Table 5.28 HHRA – T1 HQ & Risk - Off-Site Resident Receptor (Receptor #6)

a) Offsite Air (inhalation – outdoor air)

COPC*	HQ/Risk Pathway	Infant	Toddler	Child	Teen	Adult
Non-Carcinogenic Risk: HQs						
Uranium	Inhalation	3.1E-02	3.1E-02	3.1E-02	3.1E-02	3.1E-02

* Uranium is the only applicable COPC for this medium; uranium is not associated with cancer effects.

b) Offsite Soil (Incidental ingestion, dermal uptake, dust inhalation, ingestion of backyard produce)

NON-CARCINOGENIC EFFECTS						
	Infant			Toddler		
COPC*	HQi[a]	HQo+d[b]	HQt[c]	HQi[a]	HQo+d[b]	HQt[c]
Uranium	7.9E-08	2.9E-04	2.9E-04	7.9E-08	2.7E-02	2.7E-02
	Child			Teen		
COPC*	HQi[a]	HQo+d[b]	HQt[c]	HQi[a]	HQo+d[b]	HQt[c]
Uranium	7.9E-08	2.0E-02	2.0E-02	7.9E-08	1.5E-02	1.5E-02
	Adult			-		
COPC*	HQi[a]	HQo+d[b]	HQt[c]	HQi[a]	HQo+d[b]	HQt[c]
Uranium	7.9E-08	1.2E-02	1.2E-02	-	-	-

* Uranium is the only applicable COPC for this medium; uranium is not associated with cancer effects.
[a] HQi: Hazard Quotient for inhalation pathway
[b] HQo+d: Hazard Quotient for combined oral and dermal uptake pathways
[c] HQt: Hazard Quotient combined for all pathways (where applicable, see Section 5.4.2.1)

c) Offsite Surface Water (Ingestion of locally caught fish)

COPC*	HQ/Risk Pathway	Infant	Toddler	Child	Teen	Adult
Non-Carcinogenic Risk: HQs						
Uranium	Oral; Ingestion	N/A	1.3E-05	1.1E-05	6.8E-06	6.1E-06

* Uranium is the only applicable COPC for this medium; uranium is not associated with cancer effects.
N/A – Not Evaluated: not an applicable pathway for this particular receptor age category.

Table 5.29 HHRA – T1 HQ & Risk - Resident & On-site Subsurface Worker Receptor (Receptor #7)

a) Onsite Air (inhalation – outdoor air)

NON-CARCINOGENIC EFFECTS	
COPC	HQi[a]
Uranium	3.1E-02
1,1-Dichloroethylene	N/A
cis-1,2-Dichloroethene	N/A
trans-1,2-Dichloroethene	N/A
Trichloroethylene	N/A
Vinyl chloride	N/A
Chloroethane	N/A
1,1,1-Trichloroethane (TCA)	N/A
Tetrachloroethylene (PCE)	N/A
CARCINOGENIC EFFECTS	
COPC	Riski[b]
Trichloroethylene	N/A
Vinyl chloride	N/A
Tetrachloroethylene (PCE)	N/A

[a] HQi: Hazard Quotient for inhalation pathway
[b] Riski: Risk for inhalation pathway
N/C – Not Applicable

b) Soil – Onsite & Offsite (Incidental ingestion, dermal uptake, vapour inhalation, dust inhalation, ingestion of backyard produce)

NON-CARCINOGENIC EFFECTS			
COPC	HQi[a]	HQo+d[b]	HQt[c]
Uranium	2.4E-04	1.7E-02	1.7E-02
1,1-Dichloroethylene	1.0E-08	3.9E-09	1.4E-08
cis-1,2-Dichloroethene	1.1E-08	7.8E-08	N/A
trans-1,2-Dichloroethene	2.1E-08	7.8E-09	N/A
Trichloroethylene	1.0E-06	4.7E-07	N/A
Vinyl chloride	7.4E-09	6.5E-08	7.3E-08
Chloroethane	1.4E-11	N/C	N/A
1,1,1-Trichloroethane (TCA)	1.3E-09	9.8E-11	N/A
Tetrachloroethylene (PCE)	3.4E-07	2.6E-08	3.7E-07
CARCINOGENIC EFFECTS			
COPC	Riski[d]	Risko+d[e]	Riskt[f]
Trichloroethylene	5.3E-12	5.8E-12	1.1E-11
Vinyl Chloride	3.5E-12	1.5E-10	1.5E-10
Tetrachloroethylene (PCE)	1.9E-13	1.8E-13	3.7E-13

[a] HQi: Hazard Quotient for inhalation pathway
[b] HQo+d: Hazard Quotient for combined oral and dermal uptake pathways
[c] HQt: Hazard Quotient combined for all pathways (where applicable, see Section 5.4.2.1)
[d] Riski: Risk for inhalation pathway
[e] Risko+d: Risk for combined oral and dermal uptake pathways
[f] Riskt: Risk combined for all pathways (where applicable, see Section 5.4.2.1)
N/C – Not Calculated: Key parameter inputs are unavailable (e.g. concentration, TRV, etc.)
N/A – Not Applicable (see Section 5.4.2.1)

c) Offsite Surface Water (Ingestion of locally caught fish)

COPC*	HQ/Risk Pathway	Infant	Toddler	Child	Teen	Adult
Non-Carcinogenic Risk: HQs						
Uranium	Oral; Ingestion	N/A	1.3E-05	1.1E-05	6.8E-06	6.1E-06

* Uranium is the only applicable COPC for this medium; uranium is not associated with cancer effects.
N/A – Not Evaluated: not an applicable pathway for this particular receptor age category.

d) Onsite Groundwater (Incidental ingestion, groundwater vapour inhalation, dermal uptake)

NON-CARCINOGENIC EFFECTS			
COPC	HQi[a]	HQo+d[b]	HQt[c]
Uranium	NE	1.2E-02	1.2E-02
1,1-Dichloroethylene	3.4E-05	1.6E-04	1.9E-04
cis-1,2-Dichloroethene	1.8E-05	2.0E-02	N/A
trans-1,2-Dichloroethene	1.5E-05	2.9E-04	N/A
Trichloroethylene	***9.6E-01***	***3.8E+01***	N/A
Vinyl chloride	8.5E-03	***2.8E-01***	***2.8E-01***
Chloroethane	8.2E-05	NC	N/A
1,1,1-Trichloroethane (TCA)	3.4E-04	1.0E-03	N/A
Tetrachloroethylene (PCE)	3.9E-04	4.7E-03	5.1E-03
CARCINOGENIC EFFECTS			
COPC	Riski[d]	Risko+d[e]	Riskt[f]
Trichloroethylene	***4.9E-06***	***9.0E-04***	***9.1E-04***
Vinyl Chloride	***4.0E-06***	***1.2E-03***	***1.2E-03***
Tetrachloroethylene (PCE)	2.2E-10	6.3E-08	6.3E-08

Shaded values indicate exceedance of corresponding HQ (0.2) or Risk ($1x10^{-6}$) benchmark value.
[a] HQi: Hazard Quotient for inhalation pathway
[b] HQo+d: Hazard Quotient for combined oral and dermal uptake pathways
[c] HQt: Hazard Quotient combined for all pathways (where applicable, see Section 5.4.2.1)
[d] Riski: Risk for inhalation pathway
[e] Risko+d: Risk for combined oral and dermal uptake pathways
[f] Riskt: Risk combined for all pathways (where applicable, see Section 5.4.2.1)
N/C – Not Calculated: Key parameter inputs are unavailable (e.g. concentration, TRV, etc.)
N/A – Not Applicable (see Section 5.4.2.1)

Tier 2 – Non-Radiological:

Table 5.30 HHRA – T2 HQ & Risk – On-Site Maintenance Worker Receptor (Receptor #1)

a) Onsite Air (inhalation – indoor air)

NON-CARCINOGENIC EFFECTS	
COPC	HQi[a]
Uranium	**0.69**

Shaded values indicate exceedance of corresponding HQ (0.2) or Risk ($1x10^{-6}$) benchmark value.
[a] HQi: Hazard Quotient for inhalation pathway

Table 5.31 HHRA – T2 HQ & Risk - On-Site Subsurface Worker Receptor (Receptor #2)

a) Onsite Groundwater (Incidental ingestion, groundwater vapour inhalation, dermal uptake)

NON-CARCINOGENIC EFFECTS			
COPC	HQi[a]	HQo+d[b]	HQt[c]
Trichloroethylene	1.3E-01	***5.1E+00***	N/A
Vinyl chloride	1.2E-03	3.7E-02	3.8E-02
CARCINOGENIC EFFECTS			
COPC	Riski[d]	Risko+d[e]	Riskt[f]
Trichloroethylene	6.8E-07	***1.2E-04***	***1.2E-04***
Vinyl Chloride	5.4E-07	***1.6E-04***	***1.6E-04***

Shaded values indicate exceedance of corresponding HQ (0.2) or Risk ($1x10^{-6}$) benchmark value.
[a] HQi: Hazard Quotient for inhalation pathway
[b] HQo+d: Hazard Quotient for combined oral and dermal uptake pathways
[c] HQt: Hazard Quotient combined for all pathways (where applicable, see Section 5.4.2.1)
[d] Riski: Risk for inhalation pathway
[e] Risko+d: Risk for combined oral and dermal uptake pathways
[f] Riskt: Risk combined for all pathways (where applicable, see Section 5.4.2.1)
N/A – Not Applicable (see Section 5.4.2.1)

Table 5.32 HHRA – T2 HQ & Risk - Off-Site Subsurface Worker Receptor (Receptor #5)

a) Offsite Groundwater (Incidental ingestion, groundwater vapour inhalation, dermal uptake)

NON-CARCINOGENIC EFFECTS			
COPC	HQi[a]	HQo+d[b]	HQt[c]
Trichloroethylene	6.6E-04	2.6E-02	N/A
Vinyl chloride	1.6E-05	5.2E-04	5.3E-04
CARCINOGENIC EFFECTS			
COPC	Riski[d]	Risko+d[e]	Riskt[f]
Trichloroethylene	3.4E-09	6.2E-07	6.2E-07
Vinyl Chloride	7.6E-09	***2.2E-06***	***2.2E-06***

Shaded values indicate exceedance of corresponding HQ (0.2) or Risk ($1x10^{-6}$) benchmark value.

[a] HQi: Hazard Quotient for inhalation pathway
[b] HQo+d: Hazard Quotient for combined oral and dermal uptake pathways
[c] HQt: Hazard Quotient combined for all pathways (where applicable, see Section 5.4.2.1)
[d] Riski: Risk for inhalation pathway
[e] Risko+d: Risk for combined oral and dermal uptake pathways
[f] Riskt: Risk combined for all pathways (where applicable, see Section 5.4.2.1)
N/A – Not Applicable (see Section 5.4.2.1)

Table 5.33 HHRA – T2 HQ & Risk – Resident & On-Site Subsurface Worker (Receptor #7)

a) Onsite Groundwater (Incidental ingestion, groundwater vapour inhalation, dermal uptake)

NON-CARCINOGENIC EFFECTS			
COPC	HQi[a]	HQo+d[b]	HQt[c]
Trichloroethylene	1.3E-01	***5.1E+00***	N/A
Vinyl chloride	1.2E-03	3.7E-02	3.8E-02
CARCINOGENIC EFFECTS			
COPC	Riski[d]	Risko+d[e]	Riskt[f]
Trichloroethylene	6.8E-07	***1.2E-04***	***1.2E-04***
Vinyl Chloride	5.4E-07	***1.6E-04***	***1.6E-04***

Shaded values indicate exceedance of corresponding HQ (0.2) or Risk ($1x10^{-6}$) benchmark value.

[a] HQi: Hazard Quotient for inhalation pathway
[b] HQo+d: Hazard Quotient for combined oral and dermal uptake pathways
[c] HQt: Hazard Quotient combined for all pathways (where applicable, see Section 5.4.2.1)
[d] Riski: Risk for inhalation pathway
[e] Risko+d: Risk for combined oral and dermal uptake pathways
[f] Riskt: Risk combined for all pathways (where applicable, see Section 5.4.2.1)
N/A – Not Applicable (see Section 5.4.2.1)

5.4.4 Discussion

5.4.4.1 Radiological

Tier 1 calculations, based on maximum radionuclide levels in environmental media were completed. As shown in Section 5.4.3.1, all estimated Tier 1 doses are below the dose limit. Therefore, no undue radiological impacts are expected to workers or members of the public.

5.4.4.2 Non-Radiological

As shown in Section 5.4.3.2, risk and HQ results for specific receptor-media combinations were found to exceed their corresponding Tier 1 benchmark values. These receptor-media combinations were then carried forward for Tier 2 calculations. Risk and HQ exceedances in the Tier 1 and Tier 2 assessments are summarized in Table 5.34. From Table 5.34 it is clear that there are residual Tier 2 HQ and risk results that exceed their corresponding benchmark values; these residual exceedances involve:

- **TCE & VC in *onsite* groundwater:** pertaining to the on-site subsurface worker receptor, and the combined 'resident & on-site subsurface worker' receptor.
- **VC in *offsite* groundwater:** pertaining to the off-site subsurface worker receptor.
- **Uranium in *onsite* indoor air:** pertaining to the on-site maintenance worker receptor.

Table 5.34 HHRA – Summary of HQ & Risk Results (T1 and T2)

				TIER 1 Exceedances (based on max. concentration)		Tier 2 Exceedances (based on 95% UCLM Concentration)	
Receptor	**Location**	**Age**	**Media**	**HQ**	**Risk**	**HQ**	**Risk**
Maintenance	Onsite	Adult	Ind. Air	**U**	-	**U:** inhalation only (based on overall in-plant average)	-
			Soil	-	-	-	-
Sub-Surface	Onsite	Adult	Out. Air	-	-	-	-
			Soil	-	-	-	-
			GW	**TCE, VC**	**TCE, VC**	**TCE:** oral/dermal route only	**TCE, VC:** oral/dermal route only
Commercial	Offsite	Adult	Air	-	-	-	-
Maintenance	Offsite	Adult	Out.Air	-	-	-	-
			Soil	-	-	-	-
Sub-Surface	Offsite	Adult	Out. Air	-	-	-	-
			Soil	-	-	-	-
			GW	-	**TCE, VC**	-	**VC**: oral/dermal route only-
Resident	Offsite	Adult	Out. Air	-	-	-	-
			SW (fish)	-	-	-	-
			Soil	-	-	-	-
		Teen	Out. Air	-	-	-	-
			SW (fish)	-	-	-	-
			Soil	-	-	-	-
		Child	Out. Air	-	-	-	-
			SW (fish)	-	-	-	-
			Soil	-	-	-	-
		Toddler	Out. Air	-	-	-	-
			SW (fish)	-	-	-	-
			Soil	-	-	-	-
		Infant	Out. Air	-	-	-	-
			SW (fish)	-	-	-	-
			Soil	-	-	-	-
Resident + Worker	Offsite	Adult	Out.Air	-	-	-	-
			SW (fish)	-	-	-	-
	On & Off-site		Soil	-	-	-	-
	Onsite		GW	**As above: TCE, VC:** on-site subsurface worker receptor oral/dermal route only			

TCE & VC: Subsurface Receptors & Onsite/Offsite Groundwater:

The potential risks posed to onsite/offsite worker receptors from oral and dermal exposure to TCE and VC in groundwater are easily and effectively mitigated through the implementation of specific health and safety procedures (and equipment) in place at the site. This includes for example, wearing full coveralls and water-proof gloves (in particular for performing groundwater sampling activities), keeping food out of all work areas, and wearing goggles for applicable tasks. Overall, using the identified personal protection equipment (PPE) and following the existing health and safety procedures essentially eliminates exposure via these uptake routes.

For duties requiring gloves, Cameco has the appropriate type of gloves available (i.e., nitrile for laboratory work or sample collection). Respirators are required for duties that will generate dust, when air sampling indicates uranium in air, or jobs that could expose the worker to airborne contaminants.

U: Onsite Maintenance Worker Receptors & Onsite Indoor Air:

The in-plant air sampling of uranium concentration at CFM used in the risk assessment was conducted at workstations throughout the plant continuously during operations. Elevated results were reviewed by a committee regularly to identify any instances where follow up actions were required. There are also procedures at the facility requiring workers to wear respirators when performing specific job tasks in certain work areas (e.g. Compaction Room, Pangborn Room and Waste Treatment Area) (Cameco 2015a). These procedures should also apply to any non-NEWs and contractors who perform maintenance-type activities at the facility.

5.5 Uncertainties in the HHRA

Many areas of uncertainty attend a risk assessment. This is due to the fact that assumptions have to be made throughout the assessment either due to data gaps, environmental fate complexities or in the generalization of receptor characteristics. To be able to place a level of confidence in the results, an accounting of the uncertainty, the magnitude and type of which are important in determining the significance of the results, must be completed. In recognition of these uncertainties, several conservative assumptions were used throughout the assessment to ensure that the potential for an adverse effect would not be underestimated. The major assumptions are outlined below.

Exposure Point Concentrations

Measured concentrations of COPCs, and measured activities of radionuclides, were used wherever such data was available. For non-radiological COPCs, the HHRA uses the maximum and 95% UCLM concentrations from throughout the year. The use of these concentrations assumes that receptors are exposed to these higher concentrations year-round when, in reality, there is both spatial and temporal variations in concentrations. Thus, exposures are likely overestimated in the assessment.

No uranium-series radionuclides (U-238, U-234, and U-235) are directly measured. Rather, measured uranium data for environmental media focus on natural uranium levels. Therefore, the activity concentrations of uranium-series radionuclides had to be estimated as outlined in Sections 0 and 5.2.2.2. Although for HHRA this involves the use of specific activity estimates, these estimations use the maximum or 95% UCLM concentration among U_{nat} data as their starting point. It is therefore unlikely that the resulting doses would be underestimated given the use of these concentrations.

Uncertainty is also acknowledged in concentration estimates derived using modelling methodologies (i.e. predicted offsite soil uranium levels, and vapour concentrations based on COPCs in soil or groundwater). This uncertainty is due to the nature of the various input parameters used, and the degree to which they are correct, representative, and protective. To reduce uncertainty in modelling, site-specific input parameters were used wherever available – in particular for the soil accumulation modelling. Where site-specific data were not available, conservative default values were chosen; in this way the resulting estimates are unlikely to underestimate the concentrations of COPCs.

Transfer Factors

The concentration of COPCs and radionuclides in food (i.e. fish) had to be estimated using transfer factors from literature and pathways/intake calculations. There is some uncertainty involved in the use of transfer factors and data that are not site-specific; however, in the absence of measured concentrations in food, this approach provides the only method for estimating concentrations and for estimating transfer up the food chain.

Human Receptor Characterization

For all human receptors it is conservatively assumed that the incidental soil ingestion rate is constant, and that they ingest the corresponding amount of soil regardless of how much time they spend indoors (90% of the time). This would lead to a conservative overestimate of the dose they receive via this pathway.

The fraction of consumed fish that is caught locally has the potential to vary considerably. For this HHRA, it is conservatively assumed that *all* fish consumed has been caught locally (i.e. a location fraction of 1 is used). This would lead to a conservative overestimate of the dose received through the fish ingestion pathway, for applicable receptors.

For onsite maintenance worker receptors, it is conservatively assumed that they were exposed to indoor air throughout the plant, including work areas that require workers to wear respirators, two weeks per year without respirator protection. This would result in overestimating the dose received by the receptors.

For worker receptors with groundwater exposure pathways, the incidental ingestion rate for groundwater is not specified, and as such, an incidental ingestion of 10 mL of groundwater is used – this is a *very* conservative approach. Trained workers, following health and safety procedures, and wearing appropriate PPE for sampling tasks are *very* unlikely to ingest 10 mL of groundwater per exposure event. Nonetheless, this very conservative approach ensures that the resulting dose will not be underestimated.

Similarly, for worker receptors with groundwater exposure pathways, the dermal absorption period for contact with groundwater is not specified, and as such, it is assumed that dermal contact occurs throughout the entire groundwater exposure period – this is a *very* conservative approach. Trained workers, following health and safety procedures, and wearing appropriate PPE for sampling tasks are *very* unlikely to experience direct dermal contact with groundwater for the entire duration of the groundwater exposure event. Nonetheless, this very conservative approach ensures that the resulting dermal dose will not be underestimated.

Toxicity Reference Values

The TRVs are selected to be very protective. The TRVs used in the assessment were obtained from reputable sources; nonetheless, they are always associated with uncertainty due to the extrapolation of testing on lab species (e.g., rats) to humans, and due to the extrapolation from a controlled laboratory setting to real-world conditions. The use of a single value for toxicity is another area of uncertainty. The factors used in the risk assessment represent risks from maximum dose-response estimates. Also, no adjustments were made for bioavailability, which can result in either an over- or under-estimation of exposure and thus leads to uncertainty in the risk assessment.

In addition, it is important to note that toxicity data are not available for oral/dermal uptake of chloroethane (CA). This is acknowledged as a data gap.

Risk Estimation – Multiple Contaminants

In this risk assessment, it was considered that the mechanisms of action for the oral and dermal exposure routes are the same for each specific contaminant and HQs were, therefore, summed across the oral and dermal exposure routes. This is a conservative approach to dealing with oral/dermal mechanisms of action and it is therefore unlikely that risk would be underestimated by using this approach. Furthermore, for uranium, the oral, dermal, and inhalation doses have been combined since there is evidence of a common mechanism of action.

When dealing with multiple contaminants, there is a potential for interaction with other contaminants that may be encountered at the site. In addition, other factors including smoking and lifestyle factors are known to compound health effects. Synergism, potentiation, antagonism or additivity of toxic effects may occur. Some of these interactions can be handled in a simple fashion. For chemical mixtures that show additive effects based on toxicity assessment, the HQ or risk values may be added together. The lifetime risk can be expressed individually for each chemical (and by site of action, if necessary) and then totaled as a group. In practical terms, at levels of exposure typically considered in the assessment, the dose-response relation is assumed to be linear and, thus, additivity of effects (strictly by organ) is reasonable. Overall, a detailed quantitative assessment of these interactions is outside the scope of this study.

Summary

Table 5.33 provides a summary of the uncertainties discussed above. It can be seen from the table that, in general, uncertainties have been overcome by using conservative assumptions that are likely to lead to an over-estimate of exposures and thus the conclusions of the assessment would remain unchanged.

Table 5.35 HHRA – Summary of Uncertainties

Uncertainty	Likely Leads to Overestimate	Possibly Leads to Underestimate	Neither Overestimate or Underestimate
Use of transfer factors to estimate tissue concentrations	X		
Use of maximum or 95th percentile concentrations to characterize exposures	X		
Use of conservative methods to estimate concentrations where direct measurements are not available	X		
Estimation of radionuclide concentrations not directly measured			X
Incidental soil ingestion rate assumed to be constant, despite time spent indoors	X		
Assuming onsite maintenance worker exposed to indoor air throughout the plant without respirator protection.	X		
Assuming 10 mL incidental groundwater ingestion per event	X		
Assuming direct groundwater dermal contact (and resulting uptake) occurs throughout the groundwater exposure event	X		
Fraction of fish obtained locally	X		
Use of protective TRVs and maximum dose-response relationships	X		
Assuming 100% relative absorption for dermal uptake, and same mechanism of action as oral intake (i.e. combining exposures)	X		
Synergism, potentiation, antagonism, additivity of toxic effects (across multiple COPCs)		X	

6.0 ECOLOGICAL RISK ASSESSMENT

6.1 Problem Formulation

6.1.1 Receptor Selection and Characterization

For consistency, the ecological receptors included in this EcoRA are based on previous risk assessments for the CFM facility (e.g. SENES 2007), with additional species to better represent the terrestrial and aquatic environments (for example, to represent a variety of diets for terrestrial birds).

The study area encompassed by this EcoRA includes both terrestrial and aquatic environments characteristic of southern Ontario. Therefore the following major biota groups warrant consideration:

- Freshwater aquatic environment:
    - Aquatic birds;
    - Fish (benthic and pelagic);
    - Benthic invertebrates; and
    - Aquatic vegetation.
- Terrestrial environment:
    - Terrestrial birds;
    - Terrestrial mammals;
    - Terrestrial invertebrates; and
    - Terrestrial vegetation.

For each of the major biota groups mentioned above, a representative ecological receptor was selected (also referred to as an indicator species). Indicator species were selected based on:

- Knowledge of the CFM site and surrounding environment;
- Relevant environmental studies and field observations (e.g. the prior SENES 2007 study);
- Observations by CFM and Cameco staff;
- Accessibility of the environmental media; and,
- The potential species present in the area.

Table 6.1 presents the details of ecological receptor identification and selection.

Table 6.1 Identified Ecological Receptors

Major Biota Group	Potential Indicator Species
Aquatic Receptors	
Fish	• Forage/ Benthic Fish*
	• Predator/Pelagic Fish*
Benthic Invertebrates	• Benthic Invertebrates*
Aquatic Vegetation	• Macrophytes*
Aquatic Birds	• Horned Grebe
	• Lesser Scaup
Terrestrial Receptors	
Terrestrial Invertebrates	• Earthworms*
Terrestrial Vegetation	• Grass
Terrestrial Birds	• American Robin (Omnivore)
	• Great Horned Owl (Carnivore)
	• Yellow Warbler (Insectivore)
Terrestrial Mammals	• Red Fox
	• Cotton-Tail Rabbit
	• Meadow Vole

Notes:

* Assessed as general biota groups for radiological and non-radiological (chemical) EcoRA.

The following 24 representative ecological receptors have been selected:

Aquatic Receptors:

1. Forage/ Benthic Fish
2. Predator/Pelagic Fish
3. Benthic Invertebrates
4. Macrophytes
5. Lesser Scaup
6. Horned Grebe

Terrestrial Receptors

7. Earthworms
8. Vegetation (Grass)
9. American Robin (Omnivore)
10. Great Horned Owl (Carnivore)
11. Yellow Warbler (Insectivore)
12. Red Fox
13. Eastern Cotton-Tail Rabbit
14. Meadow Vole

Overall, the selected indicator species are appropriate because they reflect a variety of diets/feeding habits, cover a variety of trophic levels, are representative of the biota expected to be found in the study area, and are of interest to the facility.

Ecological characterization tables have been developed for each receptor [redacted] These profiles present receptor-specific information related to:

- Trophic level or ecosystem role (e.g., predators or prey species);
- Life history;
- Importance to humans;
- Size and body weight;
- Dietary composition;
- Food intake rate;
- Habitat;
- Habitat/home range spatial distribution and size;
- Time spent in area;
- Important behaviour and population dynamics (e.g., migratory); and
- Other useful information.

It is important to understand that fish, benthic invertebrates, terrestrial invertebrates, and vegetation (both aquatic and terrestrial) are assessed based directly on environmental concentrations. Pathways of exposure (e.g., ingestion, inhalation, etc.) are not explicitly modelled (or needed) for these receptors. As a result, ecological characterization tables [redacted] are not required for these receptors.

6.1.2 Assessment and Measurement Endpoints

Assessment endpoints

Indicator species are assessed using quantitative expressions referred to as “assessment endpoints”. These are expressions of the actual environmental values to be protected. In generally, the assessment endpoints selected in this study are healthy populations of the identified indicator species within the study area.

Measurement endpoints

Typically assessment endpoints (such as those outlined above) are qualitative in nature and do not lend themselves to direct measurement or quantification. Therefore, measurement endpoints are outlined, which are measurable or predictable expressions of the assessment endpoint.

The values of measurement endpoints will be dependent not only upon the species being protected, but also upon the level of protection provided. For example, a measurement endpoint suitable for ensuring reproductive success of a population may not be adequate to ensure the protection of each member of the population.

In this study, measurement endpoints are the screening index (SI): the ratio of an estimated exposure level (or an environmental concentration) divided by a corresponding TRV. The SI measurement endpoint is at the population level. As a result, when the chosen TRV encompasses long term effects based on survival (mortality), growth, or reproduction, then the measurement endpoint is closely linked to the assessment endpoint (healthy populations) and the necessary inferences can be made (i.e., one can infer the 'healthiness' of the population). So, where an estimated exposure level is less than the corresponding TRV (i.e., screening index less than 1), effects on a population of biota are not expected; however, where an estimated exposure level is greater than the corresponding criterion (i.e., screening index greater than 1), deleterious effects on the population of biota may or may not occur and further study may be required to determine potential effects.

6.1.3 Ecological Secondary Screening of COPCs and Stressors

Following from the results of the preliminary screening process (Section4.0), an ecological health secondary screening process is usually carried out to determine which COPCs are relevant to the EcoRA, and, to further refine the list of COPCs for risk calculations. However, all the contaminants in soil and groundwater are directly related to site operations and are found in other media so all COPCs identified in the primary screening were carried through for further consideration in the EcoRA.

6.1.4 EcoRA Exposure Pathways

Table 6.2 presents the active exposure pathways for the ecological receptors identified in Section 6.1.1. The exposure pathways are based on the known habitat needs, mobility, and diets of the ecological receptors, along with knowledge of the location of their respective habitats within the study area. *It is important to note that all surface dwelling biota (i.e. excluding submergent aquatic species, and terrestrial earthworms) are assessed for direct gamma dose, in addition to the pathways discussed below.*

Terrestrial vegetation and terrestrial invertebrates (earthworms) would be directly exposed to contaminated soil; and as such, pathways of exposure (e.g., ingestion, inhalation, etc.) are not explicitly modelled (or needed) for these receptors.

Similarly, aquatic vegetation and pelagic fish would be directly exposed to contaminated surface water. Pathways of exposure (e.g., ingestion, inhalation, etc.) are not explicitly modelled (or needed) for this receptor.

Aquatic invertebrates (benthos) and benthic fish would be directly exposed to contaminated surface water as well as sediment. Pathways of exposure (e.g., ingestion, inhalation, etc.) are not explicitly modelled (or needed) for these receptors.

Terrestrial mammals and birds are exposed through ingestion of food, including terrestrial vegetation and earthworms, as well as incidental ingestion of soil and ingestion of surface water. Higher trophic species (such as the red fox and great horned owl) will also consume lower trophic species (such as voles and robins), as part of their diet. It is assumed that terrestrial mammals and birds obtain all of their food from the site, which is conservative, given that many species have larger home ranges or forage areas than the small grass patch areas of the site. Terrestrial mammals will also receive an external dose from soil (radiological only).

Aquatic birds are exposed through ingestion of food, including aquatic vegetation and benthos, as well as ingestion of sediment and surface water. Aquatic birds will also receive an external dose from radionuclides in surface water. Higher trophic species such as the cormorant consume fish as part of their diet.

The following pathways have been identified as inactive, or are otherwise not applicable:

- *Inhalation*

As discussed in CSA N288.6 (2012), inhalation exposures are typically minor in relation to soil and food ingestion exposures, and can therefore be excluded from assessments. For particulate substances release to air and accumulating in the soil over time, the steady-state soil concentrations are usually high enough that soil and food ingestion components of dose are dominant.

- *Dermal uptake*

Dermal exposure is generally not a significant pathway of exposure for wildlife as fur and feathers are effective at blocking direct contact with skin.

- *Immersion in air (radiological only)*

External dose from immersion in air is minor, relative to soil and food ingestion exposure and can be ignored (particularly since noble gases are not identified as COPCs) (CSA 2012).

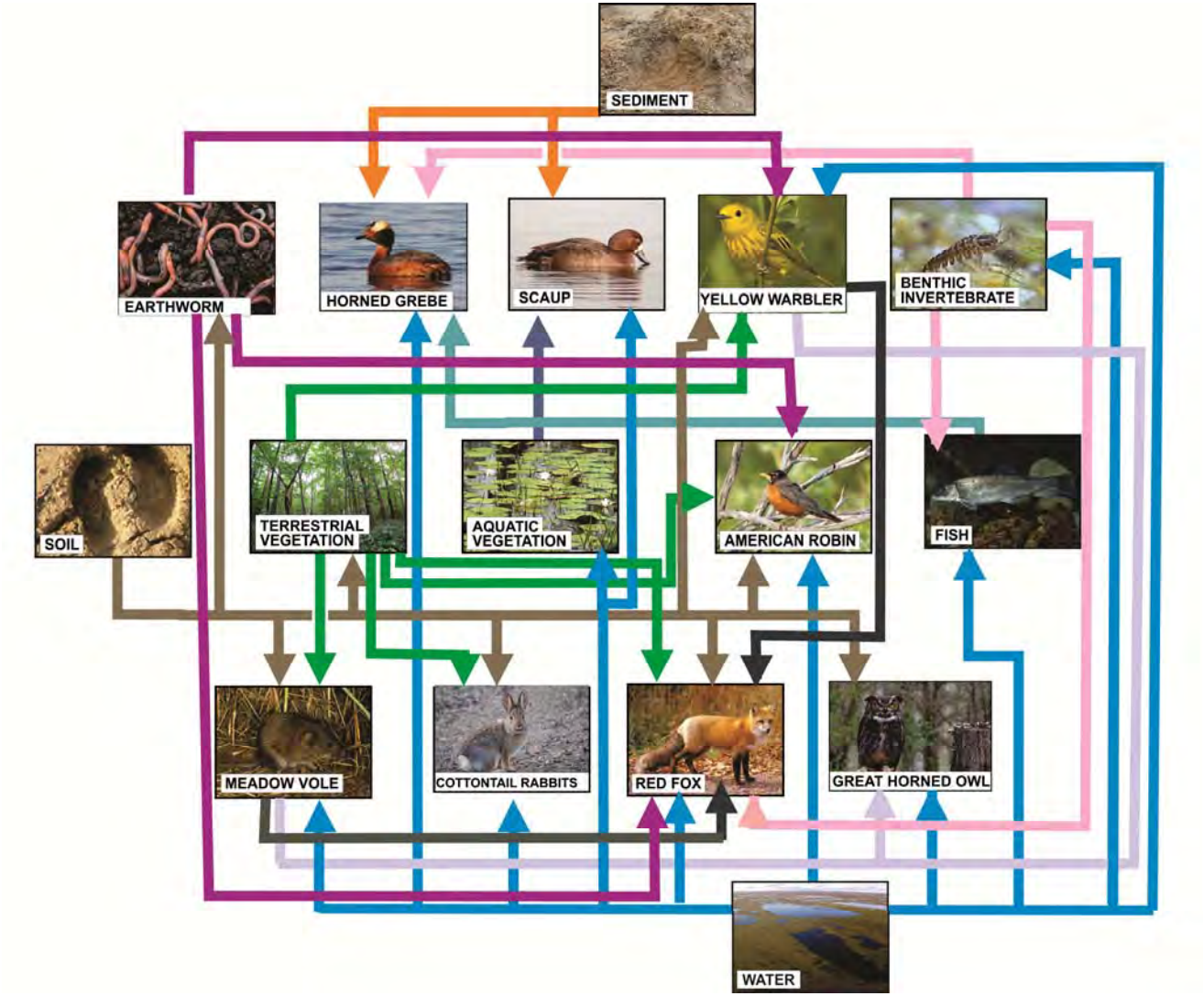
Table 6.2 EcoRA Exposure Pathways Summary

Receptor	Environmental Media Exposed	Modes of Exposure	Risk Calculation Method	
			Non-Radioactive	Radioactive
Fish	Sewage Plant Outfall • surface water • sediment	• uptake from water; • immersion in water; • exposure to sediment (benthic fish, radiological only).	Comparison of surface water concentrations with corresponding benchmark values.	**Pelagic fish:** • Internal dose from water; • External dose from water. **Benthic fish:** • Internal dose from water; • External dose from water; • External dose from sediment.
Benthic Invertebrates	Sewage Plant Outfall • surface water • sediment	• uptake from water; • immersion in water (radiological only); • immersion in sediment (radiological only).	Comparison of water concentrations with benchmark values.	• Internal dose from water; • External dose from water; • External dose from sediment.
Aquatic Plants	Sewage Plant Outfall • surface water	• uptake from water; • immersion in water (radiological only).	Comparison of water concentrations with benchmark values.	• Internal dose from water; • External dose from water.
Aquatic Birds	Sewage Plant Outfall • surface water sediment	• uptake from water; • immersion in water (radiological only); • ingestion: - aquatic vegetation; - aquatic invertebrates; - fish; - sediment;	Comparison of dose from intake with benchmark values.	• Internal dose from ingestion; • External dose from water.
Terrestrial Invertebrates	• soil • groundwater	• uptake from soil; • immersion in soil (radiological only); • uptake from groundwater; • immersion in groundwater (radiological only).	Comparison of soil or groundwater concentrations with benchmark values.	• Internal dose from soil or groundwater; • External dose from soil or groundwater.
Terrestrial Birds	• soil	• ingestion: - terrestrial vegetation; - terrestrial invertebrates; - small mammals and birds; - soil; • direct exposure to soil (radiological only).	Comparison of dose from intake with benchmark values.	• Internal dose from ingestion; • External dose from soil; • Direct gamma dose.
Terrestrial Mammals	• soil	• ingestion (as appropriate): - terrestrial invertebrates; - terrestrial vegetation; - soil; - mammals and birds (fox); • direct exposure to soil (radiological only).	Comparison of dose from intake with benchmark values.	• Internal dose from ingestion; • External dose from soil; • Direct gamma dose.
Terrestrial Plants	• soil	• uptake from soil; • exposure to soil (radiological only).	Comparison of soil concentrations with benchmark values.	• Internal dose from soil; • External dose from soil; • Direct gamma dose.

6.1.5 EcoRA Conceptual Site Model (CSM)

The overall EcoRA study boundaries are based on knowledge of the site and surrounding area, and includes a range of known and potential contamination sources. Figure 6.1 presents a schematic CSM for the site, showing the environmental media included in this EcoRA along with the exposure pathways that link these environmental media to the identified ecological receptors.

Figure 6.1 EcoRA Conceptual Site Model



6.2 Exposure Assessment

6.2.1 Exposure Points

The Tier 1 assessment relies on the conservative use of maximum concentrations in relevant environmental media, regardless of the location of the maximum measured concentrations. In this way a receptor is hypothetically/mathematically exposed to the worst-case concentrations in environmental media from several different locations simultaneously. Concentrations specific to each exposure point can be used in a Tier 2 assessment if needed, for those biota whose doses exceed their corresponding benchmarks. The maximum concentrations of COPCs in environmental media are outlined in Section 6.2.4.

6.2.2 Exposure Factors for Receptors

Table 6.3 presents an overview of key exposure factors among the ecological receptors identified and described in Section 6.1.1. [redacted]

The exposure factors for ecological receptors were obtained preferentially from Module C (*Standardization of Wildlife Receptor Characteristics*) of the Environment Canada (2012) *FCSAP Ecological Risk Assessment Guidance*.

Soil and sediment ingestion rates, if not available in the FCSAP (2012) document, were for the most part obtained from a wildlife soil ingestion study completed by Beyer *et al.* (1994) in which the fractional soil composition of the diets (i.e., percentage of the dry weight food ingestion rate) of 28 wildlife species were estimated. Ingestion rates for animals not considered in the Sample study were estimated by using fractional compositions for other animals with similar diets.

When food and water intake and inhalation rates were not available directly from the above-mentioned sources, the following allometric equations from the U.S. EPA (1993b) were used:

Dry weight food Ingestion (g dw/d):

Birds = $0.648*BW^{0.651}$ (BW in g)

Mammals = $0.235*BW^{0.822}$ (BW in g)

Water Intake (L/d):

Birds = $0.059*BW^{0.67}$ (BW in kg)

Mammals = $0.099*BW^{0.9}$ (BW in kg)

Inhalation Rate (m^3/d):

Birds = $0.4089*BW^{0.77}$ (BW in kg)

Mammals = $0.5458*BW^{0.8}$ (BW in kg)

Table 6.3 Overview of Exposure Factors for Ecological Receptors

Parameters	Units	American Robin		Great Horned Owl		Horned Grebe		Lesser Scaup		Meadow Vole		Rabbit (Eastern Cottontail)		Red Fox		Yellow Warbler	
Body Weight	g	79	1	1500	3	435	9	707	1	34.9	1	1200	5	3800	1	10	6
Water Intake Rate	L/d	0.01	1,2	0.08	2	0.03	2	0.05	1	0.007	1,2	0.12	2	0.33	1,2	0.003	2
Inhalation Rate	m3/d	0.06	2	0.56	2	0.22	2	0.31	2	0.048	2	0.63	2	1.6	2	0.012	2
Soil Ingestion Rate	g (dw)/d	0.77	1	3.8	7	-	-	-	-	0.05	1	5	2	2.8	1	0.15	7
Sediment Ingestion Rate	g (dw)/d	-	-	-	-	0.7	7	1.5	7	-	-	-	-	-	-	-	-
Food Ingestion Rate	g (dw)/d	19.2	1,2	76	2	34	2	46.4	1	2.3	1,2	79.8	2	103	1,2	2.9	2
Fraction that is small mammals	-	-	-	0.8 (Vole)	8	-	-	-	-	-	-	-	-	0.4 (Vole)	1	-	-
Fraction that is birds	-	-	-	0.2 (Y. Warbler)	8	-	-	-	-	-	-	-	-	0.2 (Y. Warbler)	1	-	-
Fraction that is invertebrates	-	0.4	1	-	-	0.5	9,11	0.9	1	-	-	-	-	0.25	1	0.9 (insects)	6
Fraction that is terrestrial vegetation	-	0.6 (berries)	1	-	-	-	-	0.1	1	1	1	1	5	0.15	1	0.1 (berries)	6
Fraction that is fish	-	-	-	-	-	0.5	9,11	-	-	-	-	-	-	-	-	-	-
Home Range	ha	0.7 to 28.3	1	230-883 (nominal: 800)	10	0.03 to 3	9	10	1	0.0069 to 0.1	1	3.1	2	280 to 3420	1	0.16	11

Notes:

1. Environment Canada 2012
2. U.S. EPA 1993b
3 Dietrich 2013
4 Handford 2001, Cornell 2011, NatureServe 2015
5 U.S. EPA 1993b, Mikita 1999, NatureServe 2015
6 Cornell 2011, NatureServe 2015, Kadlec 2003
7 Beyer *et al.* 1994
   a. great horned owl based on average soil ingestion rate of 5% of dry weight food ingestion rate for birds)
   b. lesser scaup based on average sediment ingestion rate of 2% of dry weight food ingestion rate for blue-winged teal and ring-necked duck
   c. yellow warbled based on average soil ingestion ate for non-soil/sediment dwelling birds
8 NatureServe 2015, CWS 1986, Kadlec 2003
9 Handford & Kirschbaum 2001
10 Rohner 1997, CWS 1986
11 NatureServe 2015

6.2.3 Exposure Durations and Averaging

Terrestrial Receptors

For Tier 1 and EcoRA calculations, it is conservatively assumed that ecological receptors spend their entire exposure duration within their exposure locations. In other words, there is no reduction to account for time spent outside of the exposure location.

For migratory species, risk calculations do *not* average a receptors exposure based on time away from the site during migration.

Aquatic Receptors

Similar to terrestrial EcoRA calculations, Tier 1 aquatic EcoRA calculations conservatively assume that all aquatic receptors spend their entire exposure duration within their exposure locations. In other words, there is no reduction to account for time spent outside of the exposure location.

6.2.4 Exposure Point Concentrations

Sections 6.1.4, 6.1.5, and 6.2.1 discuss the locations of ecological receptors, the environmental media that each receptor can be exposed to, and the pathway through which they can potentially be exposed.

The following tables present the concentrations for each environmental media, relevant to the identified receptors and pathways. These values are used as exposure point concentrations in subsequent exposure calculations.

Surface water concentrations used in ecological risk calculations are estimated in two different ways, resulting in two different cases:

- **Case 1:** surface water concentration is estimated based on the maximum concentration among available monitoring data, excluding monitoring stations SW4 and SW9 which are seasonally dry; and,
- **Case 2:**
    - **Tier 1:** surface water concentration is estimated for the vicinity of the municipal sewage outfall diffuser, using sewer effluent concentrations from the Cameco (2015a) *ACMOPR* with no dilution factor.
    - **Tier 2:** surface water concentration is estimated for the vicinity of the municipal sewage outfall diffuser, using sewer effluent concentrations from the Cameco (2015a) *ACMOPR* and a dilution factor of 70 to account for the dilution caused by other contributors to the total municipal effluent (see Section 3.4.1).

Table 6.4 EcoRA – Radionuclide Levels in Environmental Media

Radionuclide	Soil Concentration (Bq/kg DW)	Notes / Reference
U-234	215	Correlated from maximum measured U_{nat} concentration.
U-235	9.9	Correlated from maximum measured U_{nat} concentration.
U-238	215	Correlated from maximum measured U_{nat} concentration.
Radionuclide	**Surface Water Concentration (Case 1) (Bq/L)**	**Notes / Reference**
U-234	7.6E-02	Correlated from maximum measured U_{nat} concentration from appropriate on-site surface water monitoring stations.
U-235	3.5E-03	Correlated from maximum measured U_{nat} concentration from appropriate on-site surface water monitoring stations.
U-238	7.6E-02	Correlated from maximum measured U_{nat} concentration from appropriate on-site surface water monitoring stations.
Radionuclide	**Surface Water Concentration (Case 2, Tier 1) (Bq/L)**	**Notes / Reference**
U-234	6.3E-01	Correlated from maximum measured U_{nat} concentration in CFM effluent to municipal sewer system (Cameco 2015a).
U-235	2.9E-02	Correlated from maximum measured U_{nat} concentration in CFM effluent to municipal sewer system (Cameco 2015a).
U-238	6.3E-01	Correlated from maximum measured U_{nat} concentration in CFM effluent to municipal sewer system (Cameco 2015a).
Radionuclide	**Surface Water Concentration (Case 2, Tier 2) (Bq/L)**	**Notes / Reference**
U-234	9.0E-03	Correlated from maximum measured U_{nat} concentration, with dilution factor of 70 (see Section 3.4.1)
U-235	4.15E-04	
U-238	9.0E-03	
Radionuclide	**Groundwater Concentration (Bq/L)**	**Notes / Reference**
U-234	9.73	Correlated from maximum measured U_{nat} concentration.
U-235	4.5E-01	Correlated from maximum measured U_{nat} concentration.
U-238	9.73	Correlated from maximum measured U_{nat} concentration.
Radionuclide	**Sediment Concentration (Case 1) (Bq/kg DW)**	**Notes / Reference**
U-234	24.7	Correlated from maximum measured U_{nat} concentration.
U-235	1.14	Correlated from maximum measured U_{nat} concentration.
U-238	24.7	Correlated from maximum measured U_{nat} concentration.
Radionuclide	**Sediment Concentration (Case 2) (Bq/kg DW)**	**Notes / Reference**
U-234	31.5	Kd: CSA N288.1 (2014) Table A.26
U-235	0.45	Kd: CSA N288.1 (2014) Table A.26
U-238	31.5	Kd: CSA N288.1 (2014) Table A.26

Table 6.5 EcoRA – Non-Rad. COPC Levels in Environmental Media

COPC	Soil Concentration (mg/kg DW)	Notes / Reference
Uranium	17.4	Maximum measured concentration.
COPC	**Case 1: Surface Water Concentration (mg/L)**	**Notes / Reference**
Tetrachloroethylene	0.0005	Maximum measured concentration, excluding SW4 and SW9 (frequently dry). All results non-detect; assumed equal to detection limit.
Trichloroethylene	0.0005	
1,1-Dichloroethylene	0.0005	
trans-1,2-Dichloroethylene	0.0005	
cis-1,2-Dichlorothylene	0.0005	Maximum measured concentration among all DCE variants following MOE 2011; excluding SW4 and SW9 (frequently dry).
Chloroethane	0.0011	Maximum measured concentration plus 10% of TCE plus DCE following MOE 2011; excluding SW4 and SW9 (frequently dry).
1,1,1-Trichloroethane	0.0006	
Vinyl Chloride	0.0006	
Uranium	0.0062	Maximum measured concentration, excluding SW4 and SW9 (frequently dry)
COPC	**Case 2, Tier 1: Surface Water Concentration (mg/L)**	**Notes / Reference**
Uranium	0.051	CFM effluent concentration (no dilution factor); as described above.
COPC	**Case 2, Tier 2: Surface Water Concentration (mg/L)**	**Notes / Reference**
Uranium	0.00073	CFM effluent concentration with 70x dilution factor to account for dilution by municipal effluent (See Section 3.4.1).
COPC	**Groundwater Concentration (mg/L)**	**Notes / Reference**
1,1,1-Trichloroethane	22.7994	Maximum; Includes degradation of TCE, plus maximum DCE
1,1-Dichloroethylene	0.0829	Maximum
Chloroethane	27.6804	Maximum; Includes degradation of TCE, plus maximum DCE
cis-1,2-Dichlorothylene	0.804	Maximum
Tetrachloroethylene	0.114	Maximum
trans-1,2-Dichloroethylene	0.115	Maximum
Trichloroethylene	226	Maximum
Uranium	0.788	Maximum
Vinyl Chloride	22.8274	Maximum; Includes degradation of TCE, plus maximum DCE

6.2.4.1 Direct Gamma

Gamma dose rates used for radiological EcoRA are obtained from the CFM fenceline gamma monitoring program, as reported in the Cameco (2015a) *ACMOPR*. A maximum measured 2014 quarterly fenceline dose rate of 0.97 µSv/h (equivalent to 0.023 mGy/d) was recorded from fenceline monitoring station #12; this maximum value is used for gamma dose calculation purposes, for all biota, as a conservative measure. Furthermore, it is assumed that all ecological receptors receive this dose rate for 24 h/d (i.e. assuming 100% residency), which is conservative for several receptors.

6.2.5 Non-Radiological Dose Calculation Methods

The COPCs identified through the screening process (see Sections 4.0 and Section 6.1.3) are quantitatively evaluated for all ecological receptors (see Section 6.1.1), based on the identified pathways (see Section 6.1.4) and environmental media (see Section 6.2.4). Where sufficient data are not available, a qualitative assessment is undertaken.

Note that select biota toxicity is based on direct comparison to COPC concentrations in surrounding media; an examination of intakes is not necessary. These cases are discussed in Section 6.1.4.

For mammals and birds, COPC exposure is based on intakes, which are estimated by way of food chain intake calculations. In a broad sense, the total intake of any given COPC for a particular mammal or bird receptor is equal to the sum of intakes from all appropriate pathways, including: incidental ingestion of soil, incidental ingestion of surface water, and consumption of food (which varies based on the diet of a particular receptor). Equation 6-1 is used to calculate each of the intake routes as follows:

$$I_n = C_n \times IR_n \times f_{loc} \times CF \qquad (6\text{-}1)$$

Where:

- I_n = intake of COC via pathway “n” where “n” can represent all exposure routes such as soil, vegetation, etc. [mg/d]
- C_n = COC concentration in “n” media [mg/kg]
- IR_n = intake rate of “n” by the receptor [g/d]
- f_{loc} = fraction of time at site [-]
- CF = conversion factor 1.0×10^{-3} [kg/g]

After summing the individual intakes, the total intake was divided by the body weight of the ecological receptor in order to compare the total COC intake to the toxicity reference value (which has the unit of mg/kg-d). This is consistent with CSA (2012) methodology for calculating intakes.

6.2.6 Radiological Dose Calculation Methods

For radionuclide COPCs, the resulting radiation dose involves both internal and external components, which are calculated separately. The total radiation dose, per radionuclide, is the sum of all internal and external doses. The overall radiation dose is the total sum of all internal external doses from all radionuclides.

6.2.6.1 Aquatic Biota – Internal & External Radiation Dose

For aquatic biota, internal dose calculation is performed for each radionuclide, following Equation 6-2 (CSA 2012):

$$D_{\text{int}} = DC_{\text{int}} \times C_{tissue} \quad (6\text{-}2)$$

Where:

D_{int} = internal radiation dose [µGy/hr]
DC_{int} = internal dose coefficient for radionuclide in tissue [µGy/hr per Bq/(kg fw)]
C_{tissue} = whole body tissue concentration [Bq/(kg fw)]

External dose calculation is performed for each radionuclide, following Equation 6-3 (CSA 2012):

$$D_{ext} = DC_{ext}[(OF_{w} + 0.5 \times OF_{ws} + 0.5 \times OF_{ss}) \times C_{w} + (OF_{s} + 0.5 \times OF_{ss}) \times C_{s}] \quad (6\text{-}3)$$

Where:

D_{ext} = external radiation dose [µGy/hr]
DC_{ext} = external dose coefficient for radionuclide in water or sediment [µGy/hr per Bq/kg; or µGy/hr per Bq/L]
OF_{w} = fraction of time spent immersed in surface water [unitless]
OF_{s} = fraction of time spent immersed in sediment [unitless]
OF_{ws} = fraction of time spent on the water's surface [unitless]
OF_{ss} = fraction of time spent on the sediment's surface [unitless]
C_{w} = surface water concentration [Bq/L]
C_{s} = sediment concentration [Bq/kg]

6.2.6.2 Terrestrial Biota – Internal & External Radiation Dose

For terrestrial biota, internal dose calculation is performed for each radionuclide, following Equation 6-4 (CSA 2012):

$$D_{\text{int}} = DC_{\text{int}} \times C_{tissue} \quad (6\text{-}4)$$

Where:

D_{int} = internal radiation dose [µGy/hr]
DC_{int} = internal dose coefficient for radionuclide in tissue [µGy/hr per Bq/(kg fw)]
C_{tissue} = whole body tissue concentration [Bq/(kg fw)]

External dose calculation is performed for each radionuclide, following Equation 6-5 (CSA 2012):

$$D_{ext} = DC_{ext} \times OF_{soil} \times C_{soil} \quad (6\text{-}5)$$

Where:

D_{ext} = external radiation dose [µGy/hr]
DC_{ext} = external dose coefficient for radionuclide in soil [µGy/hr per Bq/kg]
OF_{soil} = fraction of time spent immersed in soil [unitless]
C_{soil} = soil concentration [Bq/kg]

6.2.6.3 Radiation Weighting Factors

The radioecological weighting factor, also referred to as relative biological effectiveness (RBE), is the ratio of doses from different types of radiation needed to produce the same biological effect. For example,

$$\text{Alpha RBE} = \frac{\text{(Dose of gamma to produce a given effect)}}{\text{(Dose of alpha to produce the same effect)}}$$

The RBE is applied to un-weighted doses from alpha-emitting radionuclides; the weighted doses retain their original units (i.e., mGy/day). A RBE factor of 10 is used in this study for the alpha radiation component of internal dose from all alpha emitting radionuclides, following CSA (2012). Select DCs from Prohl (2003) already include an RBE of 10 (see below), whereas DCs from Amiro (1997) are not originally weighted. In this study, an RBE of 10 has been applied to DCs for all alpha emitting radionuclides, including DCs from Amiro (1997), and DCs from Prohl (2003) that were not originally weighted.

6.2.6.4 Dose Coefficients

Radiation dose coefficients (DCs) have been selected from: (1) Prohl (2003), and (2) Amiro (1997), if an appropriate representative species could not be found in Prohl (2003), consistent with CSA (2012) guidance.

Prohl (2003) DCs

Prohl (2003) provides DCs from the FASSET program based on select reference organisms, which have been chosen by based on broad taxonomic families of organisms that are known contributors to the proper functioning of an ecosystem. The following reference organisms are considered in Prohl (2003):

Terrestrial Reference Organisms:

- Woodlouse;
- Earthworm;
- Mouse;
- Mole;
- Weasel;

- Snake;
- Rabbit;
- Red fox;
- Row deer;
- Cattle;
- Small egg;
- Big egg;
- Herbivorous bird; and
- Carnivorous bird.

Aquatic Reference Organisms Phytoplankton:

- Zooplankton;
- Crustacean;
- Insect larvae;
- Vascular plant;
- Gastropod;
- Amphibian;
- Bivalve mollusk;
- Pelagic fish;
- Benthic fish;
- Mammal; and
- Bird.

Table 6.6 presents a comparison between Prohl (FASSET) (2003) reference organism classes and the identified ecological receptors.

Table 6.6 Comparison of Ecological Receptors to Reference Organisms (for DCs)

Prohl (2003) Reference Organism	Applicable Y/N	Ecological Receptor Equivalency	Comments
Terrestrial Biota			
Earthworm	Y	Earthworm	-
Mouse	Y	Meadow Vole	Representative species
Red fox	Y	Red Fox	-
Rabbit	Y	Eastern Cotton-Tail Rabbit	Representative species
Herbivorous bird (terrestrial)	Y	American Robin Yellow Warbler	These indicator species are omnivores/insectivores (respectively). Prohl (2003) DCs are based on organism size/dimensions, not diet. According to Prohl (2003), *external* DCs for the 'carnivorous bird' reference organism are based on an organism equivalent in volume to a rabbit, whereas *external* DCs for the 'herbivorous bird' reference organism are based on an organism with volume similar to a mouse. Therefore, the herbivorous bird *external* DCs are chosen preferentially, since a mouse more closely matches the size of a robin and a yellow warbler than would a rabbit, and, the herbivorous bird *external* DCs are generally more conservative than those derived for carnivorous birds.
Carnivorous bird (terrestrial)	Y	Great Horned Owl	This indicator species is carnivorous. Prohl (2003) *external* DCs are based on organism size/dimensions, rather than diet. According to Prohl (2003), *external* DCs for the 'carnivorous bird' reference organism are based on an organism approximately equivalent in size to a rabbit. The carnivorous bird *external* DCs therefore appropriately approximate the size of the great horned owl. See further discussion below.
Terrestrial Plants - Herb (Critical Organs)	Y	Terrestrial Vegetation	See discussion below.
Aquatic Biota			
Insect larvae	Y	Benthos	Benthos includes crustaceans such as crayfish, mollusks such as clams and snails, aquatic worms and the immature (larval) forms of aquatic insects such as stonefly and mayfly nymphs. Bivalve mollusk DCs were chosen.
Gastropod			
Bivalve mollusc			
Vascular plant	Y	Aquatic Vegetation (generic)	Representative species.
Pelagic fish	Y	Pelagic Fish (generic)	Representative group.
Benthic fish	Y	Benthic Fish (generic)	Representative group.
Aquatic Bird	Y	Lesser Scaup Horned Grebe	Many representative species. Both predatory and herbivorous species are represented. The generic 'aquatic bird' DCs will be used preferentially for these receptors, where available.

As shown above, there is generally good alignment between indicator species and DC-species; however, there are two biota groups that warrant further discussion: terrestrial vegetation, and terrestrial birds.

Terrestrial Vegetation

For terrestrial vegetation, DCs for whole-body exposure are not available in Prohl (2003). Instead Prohl (2003) provides organ-specific terrestrial vegetation DCs (external) for selected critical organs of shrubs, trees and herbs (meristems and buds). By applying the DC for a sensitive critical organ to the estimated whole-body exposure, the resulting dose will have an inherent degree of conservatism. Therefore, the critical organ DC for the 'herb' reference organism was selected. Prohl (2003) does not provide internal DCs for terrestrial vegetation; to fill this data gap, internal DCs from Amiro (1997) were applied.

Terrestrial Birds

For *terrestrial* birds, DCs for *internal* exposure are not available from Prohl (2003). However, DCs derived in Prohl (2003) are primarily based on organism size (which is simplified and expressed ellipsoids or spheres of various sizes) rather than dietary composition. For *external* DCs, Prohl (2003) lists the organism size for the 'herbivorous bird' reference organism as being equal to that of the 'mouse' reference organism. Similarly, for *external* DCs Prohl (2003) lists the organism size for the 'carnivorous bird' reference organism as being equal to that of the 'rabbit' reference organism. As a result, the *internal* DCs for the 'mouse' reference organism are applied to the American Robin and Yellow Warbler receptors, whereas the *internal* DCs for the 'rabbit' reference organism are applied to the Great Horned Owl receptor.

Amiro (1997) DCs

Earthworms that live in groundwater are also not clearly defined in Prohl (2003). To maintain conservatism, DCs from Amiro (1997) were chosen as they neglect organism geometry (i.e. assume infinite size) and therefore assume that all energies emitted by radionuclides from within the biota are absorbed by the biota, regardless of its actual size.

Summary

Table 6.7 to Table 6.9 present the internal and external DCs selected for ecological receptors. Wherever a DC was not originally weighted in its source reference - and therefore has an RBE of 10 applied – this has been indicated.

For external soil DC selection, the rabbit, fox and meadow vole are burrowing animals and therefore DCs for biota that reside "in soil" were used preferentially over DCs for biota that reside "on soil".

Table 6.7 EcoRA: Dose Coefficients – Internal

Biota	Radionuclide	DC (weighted) (Gy/y per Bq/kgFW)	Reference
American Robin	U-234	2.37E-04	Prohl (2003); T 3-13; Mouse
American Robin	U-235	2.28E-04	Prohl (2003); T 3-13; Mouse
American Robin	U-238	2.10E-04	Prohl (2003); T 3-13; Mouse
Aquatic Vegetation	U-234	2.37E-04	Prohl (2003); T4-7; Vascular Plant RBE=10
Aquatic Vegetation	U-235	2.28E-04	Prohl (2003); T4-7; Vascular Plant RBE=10
Aquatic Vegetation	U-238	4.64E-04	Prohl (2003); T4-7; Vascular Plant RBE=10
Benthic Fish	U-234	2.37E-04	Prohl (2003); T4-7; Benthic Fish RBE=10
Benthic Fish	U-235	2.28E-04	Prohl (2003); T4-7; Benthic Fish RBE=10
Benthic Fish	U-238	4.99E-04	Prohl (2003); T4-7; Benthic Fish RBE=10
Benthos	U-234	2.37E-04	Prohl (2003); T4-7; Bivalve Mollusc RBE=10
Benthos	U-235	2.28E-04	Prohl (2003); T4-7; Bivalve Mollusc RBE=10
Benthos	U-238	4.99E-04	Prohl (2003); T4-7; Bivalve Mollusc RBE=10
Cottontail Rabbit	U-234	2.37E-04	Prohl (2003); T3-13; Rabbit
Cottontail Rabbit	U-235	2.28E-04	Prohl (2003); T3-13; Rabbit
Cottontail Rabbit	U-238	2.10E-04	Prohl (2003); T3-13; Rabbit
Earthworm (soil)	U-234	2.37E-04	Prohl (2003); T3-13; Earthworm
Earthworm (soil)	U-235	2.28E-04	Prohl (2003); T3-13; Earthworm
Earthworm (soil)	U-238	2.10E-04	Prohl (2003); T3-13; Earthworm
Great Horned Owl	U-234	2.37E-04	Prohl (2003); T3-13; Rabbit
Great Horned Owl	U-235	2.28E-04	Prohl (2003); T3-13; Rabbit
Great Horned Owl	U-238	2.10E-04	Prohl (2003); T3-13; Rabbit
Horned Grebe	U-234	2.37E-04	Prohl (2003); T4-7; Bird RBE=10
Horned Grebe	U-235	2.37E-04	Prohl (2003); T4-7; Bird RBE=10
Horned Grebe	U-238	4.99E-04	Prohl (2003); T4-7; Bird RBE=10
Lesser Scaup	U-234	2.37E-04	Prohl (2003); T4-7; Bird RBE=10
Lesser Scaup	U-235	2.37E-04	Prohl (2003); T4-7; Bird RBE=10
Lesser Scaup	U-238	4.99E-04	Prohl (2003); T4-7; Bird RBE=10
Meadow Vole	U-234	2.37E-04	Prohl (2003); T 3-13; Mouse
Meadow Vole	U-235	2.28E-04	Prohl (2003); T 3-13; Mouse
Meadow Vole	U-238	2.10E-04	Prohl (2003); T 3-13; Mouse
Pelagic Fish	U-234	2.37E-04	Prohl (2003); T4-7; Pelagic Fish RBE=10
Pelagic Fish	U-235	2.28E-04	Prohl (2003); T4-7; Pelagic Fish RBE=10
Pelagic Fish	U-238	4.99E-04	Prohl (2003); T4-7; Pelagic Fish RBE=10
Red Fox	U-234	2.37E-04	Prohl (2003); T 3-13; Red Fox
Red Fox	U-235	2.28E-04	Prohl (2003); T 3-13; Red Fox
Red Fox	U-238	2.10E-04	Prohl (2003); T 3-13; Red Fox
Vegetation	U-234	2.46E-04	Amiro (1997); RBE=10
Vegetation	U-235	2.36E-04	Amiro (1997); RBE=10
Vegetation	U-238	2.16E-04	Amiro (1997); RBE=10
Yellow Warbler	U-234	2.37E-04	Prohl (2003); T3-13; Mouse
Yellow Warbler	U-235	2.28E-04	Prohl (2003); T3-13; Mouse
Yellow Warbler	U-238	2.10E-04	Prohl (2003); T3-13; Mouse

Table 6.8 EcoRA: Dose Coefficients – External from Water

Biota	Radionuclide	DC (Gy/y per Bq/m3)	Reference
Aquatic Vegetation	U-234	1.58E-11	Prohl (2003); T4-8; Vascular Plant
Aquatic Vegetation	U-235	1.14E-09	Prohl (2003); T4-8; Vascular Plant
Aquatic Vegetation	U-238	4.12E-09	Prohl (2003); T4-8; Vascular Plant
Benthic Fish	U-234	3.07E-12	Prohl (2003); T4-8; Benthic Fish
Benthic Fish	U-235	7.27E-10	Prohl (2003); T4-8; Benthic Fish
Benthic Fish	U-238	2.80E-10	Prohl (2003); T4-8; Benthic Fish
Benthic Invertebrates	U-234	3.59E-12	Prohl (2003); T4-8; Bivalve Mollusc
Benthic Invertebrates	U-235	8.06E-10	Prohl (2003); T4-8; Bivalve Mollusc
Benthic Invertebrates	U-238	4.64E-10	Prohl (2003); T4-8; Bivalve Mollusc
Horned Grebe	U-234	1.66E-09	Prohl (2003); T4-8; Bird
Horned Grebe	U-235	5.87E-07	Prohl (2003); T4-8; Bird
Horned Grebe	U-238	1.66E-07	Prohl (2003); T4-8; Bird
Lesser Scaup	U-234	1.66E-09	Prohl (2003); T4-8; Bird
Lesser Scaup	U-235	5.87E-07	Prohl (2003); T4-8; Bird
Lesser Scaup	U-238	1.66E-07	Prohl (2003); T4-8; Bird
Pelagic Fish	U-234	3.42E-12	Prohl (2003); T4-8; Pelagic Fish
Pelagic Fish	U-235	7.88E-10	Prohl (2003); T4-8; Pelagic Fish
Pelagic Fish	U-238	3.85E-10	Prohl (2003); T4-8; Pelagic Fish

Table 6.9 EcoRA: Dose Coefficients – External from Soil/Sediment

Biota	Radionuclide	DC (Gy/y per Bq/kgDW)	Reference
American Robin	U-234	4.38E-10	Prohl (2003); T3-9; Herbivorous Bird
American Robin	U-235	2.37E-07	Prohl (2003); T3-9; Herbivorous Bird
American Robin	U-238	2.80E-10	Prohl (2003); T3-9; Herbivorous Bird
Benthic Fish	U-234	1.21E-08	Amiro (1997)
Benthic Fish	U-235	9.95E-07	Amiro (1997)
Benthic Fish	U-238	9.48E-09	Amiro (1997)
Benthos	U-234	1.21E-08	Amiro (1997)
Benthos	U-235	9.95E-07	Amiro (1997)
Benthos	U-238	9.48E-09	Amiro (1997)
Cottontail Rabbit	U-234	8.67E-10	Prohl (2003); T3-9; Rabbit
Cottontail Rabbit	U-235	2.28E-07	Prohl (2003); T3-9; Rabbit
Cottontail Rabbit	U-238	6.39E-10	Prohl (2003); T3-9; Rabbit
Earthworm (soil)	U-234	2.54E-10	Prohl (2003); T3-10; Earthworm
Earthworm (soil)	U-235	2.54E-07	Prohl (2003); T3-10; Earthworm
Earthworm (soil)	U-238	1.31E-10	Prohl (2003); T3-10; Earthworm
Great Horned Owl	U-234	1.75E-10	Prohl (2003); T3-9; Carnivorous Bird
Great Horned Owl	U-235	1.93E-07	Prohl (2003); T3-9; Carnivorous Bird
Great Horned Owl	U-238	8.23E-11	Prohl (2003); T3-9; Carnivorous Bird
Horned Grebe	U-234	1.21E-08	Amiro (1997)
Horned Grebe	U-235	9.95E-07	Amiro (1997)
Horned Grebe	U-238	9.48E-09	Amiro (1997)
Lesser Scaup	U-234	1.21E-08	Amiro (1997)
Lesser Scaup	U-235	9.95E-07	Amiro (1997)
Lesser Scaup	U-238	9.48E-09	Amiro (1997)
Meadow Vole	U-234	2.54E-10	Prohl (2003); T3-10; Mouse
Meadow Vole	U-235	2.54E-07	Prohl (2003); T3-10; Mouse
Meadow Vole	U-238	1.31E-10	Prohl (2003); T3-10; Mouse
Red Fox	U-234	7.71E-10	Prohl (2003); T3-9; Red Fox
Red Fox	U-235	2.10E-07	Prohl (2003); T3-9; Red Fox
Red Fox	U-238	5.69E-10	Prohl (2003); T3-9; Red Fox
Vegetation	U-234	1.05E-09	Prohl (Herb)
Vegetation	U-235	2.72E-07	Prohl (Herb)
Vegetation	U-238	7.80E-10	Prohl (Herb)
Yellow Warbler	U-234	4.38E-10	Prohl (2003); T3-9; Herbivorous Bird
Yellow Warbler	U-235	2.37E-07	Prohl (2003); T3-9; Herbivorous Bird
Yellow Warbler	U-238	2.80E-10	Prohl (2003); T3-9; Herbivorous Bird

6.2.7 Transfer Factors

Overall, the selection of transfer factors follows the CSA N288.6 (2012) recommended hierarchy sources for Transfer Factors (TFs) and Concentration Ratios (CRs).

To estimate intake up the food chain, concentrations of COPCs in terrestrial vegetation, earthworms and small mammals (as prey) are estimated using transfer factors (TFs) from literature sources (namely those recommended by CSA (2012)). The associated tissue concentrations in terrestrial vegetation, earthworms and small mammals from all exposure pathways are estimated from soil concentrations as shown in Equation 6-6:

$$C_{biota} = C_{soil} \times TF_{soil\text{-}to\text{-}biota} \quad (6\text{-}6)$$

Where:

C_{biota} = COC concentration in biota (vegetation, earthworms, small mammals) [mg/(kg ww)]

C_{soil} = COC concentration in soil [mg/(kg dw)]

TF = transfer factor from soil-to-biota [(mg/(kg ww))/(mg/(kg dw))]

Soil-to-small mammal transfer factors are not always available for all COPCs. As an alternative, mammalian tissue concentrations can also be estimated from allometrically scaled feed-to-tissue transfer factors as shown in Equation 6-7:

$$C_{tissue} = I_{total} \times TF_{feed\text{-}to\text{-}tissue} \quad (6\text{-}7)$$

Where:

C_{tissue} = COC concentration in tissue of ingested animal [mg/(kg ww)]

I_{total} = intake of COC by ingested animal from all pathways ($\sum I_n$) [mg/d]

$TF_{feed\text{-}to\text{-}tissue}$ = allometrically scaled transfer factor from feed-to-tissue [d/kg]

Transfer factors from literature for feed-to-beef (cow) are available for many COPCs, which can then be allometrically scaled for the ingested mammal using the ratio of their body weight to that of the cow using Equation 6-8:

$$TF_{sm} = TF_{fb} \times \left(\frac{BW_{sm}}{BW_{cow}} \right)^{-0.75} \quad (6\text{-}8)$$

Where:

TF_{sm} = feed-to-tissue transfer factor for small mammal [d/(kg ww)]

TF_{fb} = feed-to-tissue transfer factor for beef [d/(kg ww)]

BW_{sm} = body weight of small mammal [kg]

BW_{cow} = 600, body weight of cow [kg] (CSA 2014 Table G.7)

Similarly, transfer factors from literature for feed-to-bird (poultry) can be allometrically scaled for the ingested birds using the ratio of their body weight to that of the poultry using Equation 6-9:

$$TF_{bird} = TF_{poultry} \times \left(\frac{BW_{bird}}{BW_{poultry}} \right)^{-0.75} \quad (6\text{-}8)$$

Where:

TF_{bird} = feed-to-tissue transfer factor for bird [d/(kg ww)]

$TF_{poultry}$ = feed-to-tissue transfer factor for poultry [d/(kg ww)]

BW_{bird} = body weight of bird [kg]

$BW_{poultry}$ = 2, body weight of poultry [kg] (CSA 2014 Table G.7)

Table 6.10 presents the transfer factors selected for the EcoRA. For terrestrial plants, a moisture content of 81% was used for converting between dry weight (DW) and wet weight (WW or FW).

Table 6.10 EcoRA: Transfer Factors

a) Aquatic Receptors

Factor	Uranium	Reference
Sediment-Water Kd (L/kg)	50	CSA N288.1 (2014), Table A.26 for shoreline sediments
Aquatic Vegetation-Water TF (L/kg FW)	1100	CSA N288.1 (2014), Table A.25f for freshwater plants
Benthos-Water TF (L/kg FW)	110	CSA N288.1 (2014), Table A.25e, for freshwater invertebrates
Fish-Water TF (L/kg FW)	2.4	IAEA (2010), Table 57 (mean) for freshwater fish, whole
Feed-to-Bird TF (d/kg FW)	0.75	CSA N288.1 (2014), Table G.3, value for poultry meat

b) Terrestrial Receptors

Factor	Uranium	Reference
Soil-Water Kd (m^3/kgDW)	0.11	CSA N288.1 (2014), Table G.2 (sand)
Earthworm-Soil TF (g DW /g DW)	0.033	Sample *et al.* 1998 (Appendix C.1; Table C.1, Median)
Vegetation-Soil TF (g DW /g DW)	0.01	CSA N288.1 (2014), Table G.3 (CR)
Feed-to-Bird TF (d/kg FW)	0.75	CSA N288.1 (2014), Table G.3, value for poultry meat
Feed-to-Mammal TF (d/kg FW)	0.00039	CSA N288.1 (2014), Table G.3, value for beef meat

6.3 Effects Assessment

6.3.1 Non-Radiological COPCs – Benchmark Values

Overall, the non-radiological COPCs that require toxicity reference values (TRVs) for quantitative assessment include uranium, TCE, 1,1-DCE, 1,2-DCE (cis and trans isomers), tetrachloroethylene, chloroethane, and vinyl chloride. While uranium TRV information is available from several sources, ecological TRVs for many of the chlorinated organics are limited.

6.3.1.1 Uranium

The selection of uranium TRVs generally incorporates CSA N288.6 guidance (CSA 2012), but in cases where N288.6 sources are considered outdated, values from more recent credible sources are used preferentially (with supporting rationale).

For mammals and birds, TRVs were primarily obtained from the SENES & EcoMetrix (2012) *Compilation and Critical Review of Toxicity Reference Values for Use in Risk Assessments for Cameco Facilities in Canada*, which includes information from Sample *et al.* (1996), and represents the most recent and comprehensive TRV information for Cameco sites available at this time. In SENES & EcoMetrix (2012), dose-based TRVs for wildlife were derived from a review of data presented in the documentation of U.S. EPA risk-based ecological soil screening levels (Eco-SSLs) for most analytes, and literature studies were reviewed for chronic dose values for analytes without Eco-SSL data. Endpoints involving growth and reproduction were considered to be relevant to assessment of wildlife populations. TRV were derived preferentially from LOAEL data. The use of LOAELs is consistent with CSA (2012), which states that selected benchmarks should correspond to the lowest exposure levels (e.g., LOAELs) associated with adverse effects. A comparison was made to mortality based endpoints to ensure that the derived TRV does not exceed a mortality endpoint. Where available, the LOAELs were paired with NOAELs for reference purposes. An important aspect of the SENES & EcoMetrix (2012) is the avoidance of allometric scaling. Historically, the results of toxicity tests on laboratory animals, which were typically limited to test species, were adjusted for other species by applying allometric equations for weight differences between test species and species of interest in the assessment. More

recently, the allometric weight adjustment was found to be inappropriate for most analytes and ecological receptors. Therefore, the approach is instead to find toxicity data for species that most closely represent a given ecological receptor in a particular assessment (i.e., use of surrogates) in terms of diet and overall organism size. For uranium, only a single study was available for mammals (mouse) and birds (black duck), and so these studies were used for all mammals and birds (aquatic and terrestrial), respectively. For more detailed description of the TRV derivation process and the toxicity data used, the reader is referred to the original SENES & EcoMetrix (2012) report.

For aquatic vegetation, invertebrates, and fish, TRVs were also obtained from SENES & EcoMetrix (2012). For these aquatic biota, the TRV information in SENES & EcoMetrix (2012) is ultimately based on data from the United States Environmental Protection Agency (U.S. EPA) ECOTOXicology database (ECOTOX). This database reports toxicity data for a wide range of aquatic species as well as laboratory and field studies. For most chemicals, ECOTOX includes toxicity data in literature from 1972 to the present. All data have been quality assured according to the U.S. EPA's criteria, and the system is updated quarterly (U.S. EPA 2012). CSA (2012) also supports the use of ECOTOX as a source of information. The following principles were applied in the selection of toxicity data for aquatic biota:

- Endpoints involving growth, reproduction and survival were considered to be relevant to persistence of aquatic populations (consistent with CSA 2012);
- Only freshwater toxicity studies were considered;
- Records without test duration, endpoint and exposure concentration were eliminated;
- Chronic toxicity data were preferred in the selection (favoured by CSA 2012 as well). When chronic data were not sufficient (minimum of 2), acute data were considered and converted to chronic values;
- Chronic EC20 concentrations were preferred (consistent with CSA 2012). If not reported, other endpoints were considered and adjusted to an estimated EC20 value (see discussion below).

If more than 20 chronic EC20 were available in each taxonomic group, a 5th percentile of the EC20 distribution was used as a recommended TRV; if there were less than 20 chronic EC20 values, the lowest EC20 was used as a recommended TRV for the taxonomic category. The lowest chronic EC20 or 5th percentile of chronic EC20s derived from the above process were compared with widely used TRVs in ecological risk assessment recommended by Suter and Tsao (1996), U.S. EPA, CCME or other government guideline documents. The more appropriate values were selected as the recommended TRV for each taxonomic category in this review. For details regarding the TRV derivations and modifying factors for each individual COPC, the reader is referred to the original SENES & EcoMetrix (2012) study.

For terrestrial vegetation and terrestrial invertebrates (earthworms), TRV information is not available in the SENES & EcoMetrix (2012) document. As such, a review was conducted of the MOE (2011b) rationale document, the soil quality standards of the CCME, the Eco-SSL documents of the U.S. EPA, along with values from the Environment Canada (2013) Database of Guidelines. The MOE considers ecotoxicity criteria in the development of soil criteria, so that soil standards are protective of both human and ecological health. In the MOE update of their soil criteria (2011b), plant and soil invertebrate protection values for agricultural/residential/parkland and industrial/commercial land use were developed following the CCME

(1996) protocol using current scientific literature data on toxicity to agricultural crops, native plant species and soil dwelling organisms. It is commonly acknowledged that the level of protection for plants and soil organisms can be less stringent for commercial/industrial land use than for agricultural/residential/parkland land use. However, in following the CCME (1996) protocol, this was problematic for no/lowest observable effects concentration (NOEC/LOEC) data (a combined NOEC/LOEC dataset was used for the agricultural/residential/parkland derivation, while an LOEC-only dataset was used for the commercial/industrial derivation which can throw out useful information and thereby drive the value down). To solve this issue, the MOE used a combined NOEC/LOEC dataset for both land uses, and selected the 25th and 50th percentile values as the agricultural/residential/parkland and industrial/commercial protection values, respectively. In situations where a value for plant and soil organism protection could not be developed for industrial/commercial land use, the MOE applied a factor of 2 to the agricultural/residential/parkland value. This was felt to be sufficiently protective for an industrial/commercial setting. It was determined that the above-described MOE approach was appropriate for use in the current assessment and thus, the MOE values for protection of plants and soil invertebrates were selected as the TRVs when available.

Following the above methodology, the MOE was able to develop components values for 20 constituents. The MOE also reviewed information from other jurisdictions and found that CCME ecological protection numbers and the numbers developed by the Netherlands would provide a suitable level of protection for Ontario. The Netherlands criteria were derived using the 50th percentile of the "No Observed Effect Distribution" (NOEC) of the data.

Table 6.11 summarize the TRVs selected for mammals and birds. Table 6.12 summarizes the TRVs selected for aquatic vegetation, aquatic invertebrates and fish. Table 6.13 summarizes the TRV selected for terrestrial invertebrates and terrestrial vegetation.

Table 6.11 EcoRA - Uranium TRVs: Mammals & Birds (mg/kg-d)

COPCs	Test Species	LOAEL Data	Final TRV	Ecological Receptor	Comments
MAMMALS					
U	Mouse	5.6 [a]	5.6 [a]	Cotton-Tail Rabbit Red Fox Meadow Vole	Sample *et al.* (1996) *Based on a single study NOAEL (LOAEL not available), with correction for unit conversion error in Sample et al. (1996).*
BIRDS					
U	Black Duck	[a]	16 [a]	American Robin Yellow Warbler Great Horned Owl Lesser Scaup Horned Grebe	Sample *et al.* (1996) *Based on a single study NOAEL (LOAEL not available).*

Table 6.12 EcoRA - Uranium TRVs: Aquatic Vegetation, Aquatic Invertebrates, and Fish (mg/L)

COPCs	Final TRV	Ecological Receptor	Reference
U	1.5	Fish (benthic)	1
	0.55	Fish (pelagic)	1
	5.5	Aquatic Vegetation	1
	0.027	Benthic Invertebrates	1

Notes:
[1] SENES & EcoMetrix (2012)

Table 6.13 EcoRA Uranium TRVs: Terrestrial Plants & Earthworms (mg/kg)

COPCs	Terrestrial Invertebrates (Earthworm)	Terrestrial Vegetation
Uranium	2,000 [a]	2,000 [a]

Notes:
[a] MOE (2011) direct soil contact protection value for *industrial* land use.

6.3.1.2 Chlorinated Organics

Overall, ecological receptor TRVs for chlorinated organics are limited. TRV information from the CCME online database of water quality guidelines were selected, as they are readily available and credible. TRVs could not be found for mammals, birds, terrestrial vegetation, or terrestrial invertebrates.

The CCME (2015a) online database of water quality guidelines recommends a value of 0.021 mg/L TCE for protection of freshwater aquatic life. This value is based on the CCME (1999) review of toxicity data for TCE and freshwater species, mainly involving: 24 to 96-hour LC_{50} toxicity test results for fish species such as juvenile American flagfish, golden orfes, fathead minnows, and rainbow trout; chronic toxicity data for brook trout and flagfish; and 48-hr EC_{50} toxicity data for water fleas. Therefore, the 0.021 mg/L TCE TRV has been selected for aquatic vegetation, fish (benthic and pelagic), and benthic invertebrates. The CCME (2015a) online database of water quality guidelines recommends a value of 0.110 mg/L PCE (1,1,2,2-tetrachloroethylene) for protection of aquatic life, though a detailed factsheet is not available.

Table 6.14 summarizes the TRVs obtained for chlorinated organics.

Table 6.14 EcoRA: TRVs for Chlorinated Organics (CCME 2015a, online)

COPC	TRV	Units	Test Species	Applicable Ecological Receptors	Reference
TCE	0.021	mg/L	Flagfish Golden Orfe Fathead Minnow Rainbow Trout Brook Trout Water Flea	Aquatic Vegetation Benthic Fish Pelagic Fish Benthos	CCME 1999
PCE (1,1,2,2-Tetra chloroethene)	0.110	mg/L	-	Aquatic Vegetation Benthic Fish Pelagic Fish Benthos	CCME 1993

6.3.2 Radiological Dose Benchmarks

Radiological dose benchmarks from CSA (2012) are used preferentially (i.e. 100 and 400 µGy/hr). These values are also broadly consistent with the SENES & EcoMetrix (2012) *Compilation and Critical Review of Toxicity Reference Values for Use in Risk Assessments for Cameco Facilities in Canada* interpretation and conclusions regarding radiation dose benchmarks for biota. SENES & EcoMetrix (2012) consolidates and compares information from a wide range of sources, including:

- IAEA;
- UNSCEAR;
- NCRP;
- US DOE;
- UK EA; and
- EC/HC.

Table 6.15 presents a breakdown by indicator species of the radiological dose benchmarks selected for all aquatic and terrestrial biota.

Table 6.15 EcoRA Radiological Dose Benchmarks (mGy/d) [*CSA (2012)*]

Category	Organism	Dose Rate Benchmark
Aquatic Biota	Fish (benthic & pelagic)	9.6 mGy/d
	Aquatic Vegetation	9.6 mGy/d
	Benthic Invertebrates	9.6 mGy/d
	Aquatic Birds	9.6 mGy/d
Terrestrial Biota	Terrestrial Animals	2.4 mGy/d
	Terrestrial Plants	2.4 mGy/d

6.4 Risk Characterization

This section presents the risk results (SIs) calculated for each receptor-COPC combination, based on a comparison of estimated exposures to the toxicity and radiation benchmarks outlined in Section 6.3.

Overall, both radiological and non-radiological risk are assessed using two (2) cases, as described in Section 6.2.4.

6.4.1 Risk Results – Radiological

Tier 1 (Case 1 and Case 2)

Table 6.16 presents Case 1 radiological dose estimates for terrestrial receptors, whereas Table 6.17 presents Case 1 radiological dose estimates for aquatic receptors. The corresponding dose benchmark is shown, along with a SI comparison. Table 6.18 and Table 6.19 present Case 2 radiological dose estimates for terrestrial and aquatic receptors, respectively.

TIER 1: Case 1

Table 6.16 EcoRA Radiological Dose (mGy/d) & SI Results (Terrestrial) [Tier 1, Case 1]

Radionuclide	American Robin	Cotton-Tail Rabbit	Earthworm (Soil)	Great Horned Owl	Meadow Vole	Red Fox	Terr. Vegetation	Yellow Warbler
U-234	1.0E-02	3.4E-05	2.1E-02	7.2E-04	6.3E-06	7.6E-05	2.8E-04	1.5E-02
U-235	4.5E-04	7.7E-06	9.3E-04	3.7E-05	7.2E-06	9.0E-06	2.0E-05	6.9E-04
U-238	9.0E-03	3.0E-05	1.9E-02	6.3E-04	5.5E-06	6.7E-05	2.4E-04	1.4E-02
Gamma (mGy/d)	2.3E-02	2.3E-02	2.3E-02	2.3E-02	2.3E-02	2.3E-02	2.3E-02	2.3E-02
Total (mGy/d)	**4.3E-02**	**2.3E-02**	**6.3E-02**	**2.3E-02**	**2.4E-02**	**2.3E-02**	**2.4E-02**	**5.3E-02**
ENEV (mGy/d)	**2.4**	**2.4**	**2.4**	**2.4**	**2.4**	**2.4**	**2.4**	**2.4**
SI (-)	*0.018*	*0.010*	*0.026*	*0.010*	*0.010*	*0.010*	*0.010*	*0.022*

Table 6.17 EcoRA Radiological Dose (mGy/d) & SI Results (Aquatic) [Tier 1, Case 1]

Radionuclide	Aq. Vegetation	Benthic Fish	Benthos	Horned Grebe	Lesser Scaup	Pelagic Fish
U-234	5.5E-02	1.2E-04	5.5E-03	2.5E-04	8.3E-04	1.2E-04
U-235	2.4E-03	6.8E-06	2.4E-04	1.2E-05	3.8E-05	5.3E-06
U-238	1.1E-01	2.5E-04	1.2E-02	5.3E-04	1.8E-03	2.5E-04
Gamma (mGy/d)	2.3E-02	2.3E-02	2.3E-02	2.3E-02	2.3E-02	2.3E-02
Total (mGy/d)	**1.9E-01**	**2.3E-02**	**4.0E-02**	**2.4E-02**	**2.6E-02**	**2.3E-02**
ENEV (mGy/d)	**9.6**	**9.6**	**9.6**	**9.6**	**9.6**	**9.6**
SI (-)	*0.020*	*0.002*	*0.004*	*0.002*	*0.003*	*0.002*

TIER 1: Case 2

Table 6.18 EcoRA Radiological Dose (mGy/d) & SI Results (Terrestrial) [Tier 1, Case 2]

Radionuclide	American Robin	Cotton-Tail Rabbit	Earthworm (Soil)	Great Horned Owl	Meadow Vole	Red Fox	Terr. Vegetation	Yellow Warbler
U-234	1.0E-02	3.6E-05	2.1E-02	7.4E-04	7.8E-06	7.8E-05	2.8E-04	1.5E-02
U-235	4.6E-04	7.7E-06	9.3E-04	3.8E-05	7.2E-06	9.1E-06	2.0E-05	6.9E-04
U-238	9.0E-03	3.2E-05	1.9E-02	6.6E-04	6.9E-06	6.9E-05	2.4E-04	1.4E-02
Gamma (mGy/d)	2.3E-02	2.3E-02	2.3E-02	2.3E-02	2.3E-02	2.3E-02	2.3E-02	2.3E-02
Total (mGy/d)	**4.3E-02**	**2.3E-02**	**6.3E-02**	**2.4E-02**	**2.3E-02**	**2.3E-02**	**2.4E-02**	**5.3E-02**
ENEV (mGy/d)	**2.4**	**2.4**	**2.4**	**2.4**	**2.4**	**2.4**	**2.4**	**2.4**
SI (-)	*0.018*	*0.010*	*0.026*	*0.010*	*0.010*	*0.010*	*0.010*	*0.022*

Table 6.19 EcoRA Radiological Dose (mGy/d) & SI Results (Aquatic) [Tier 1, Case 2]

Radionuclide	Aq. Vegetation	Benthic Fish	Benthos	Horned Grebe	Lesser Scaup	Pelagic Fish
U-234	4.5E-01	9.8E-04	4.5E-02	1.9E-03	6.6E-03	9.8E-04
U-235	2.0E-02	4.5E-05	2.0E-03	8.7E-05	3.0E-04	4.4E-05
U-238	8.8E-01	2.1E-03	9.5E-02	4.0E-03	1.4E-02	2.1E-03
Gamma (mGy/d)	2.3E-02	2.3E-02	2.3E-02	2.3E-02	2.3E-02	2.3E-02
Total (mGy/d)	**1.4E+00**	**2.6E-02**	**1.6E-01**	**2.9E-02**	**4.4E-02**	**2.6E-02**
ENEV (mGy/d)	**9.6**	**9.6**	**9.6**	**9.6**	**9.6**	**9.6**
SI (-)	*0.143*	*0.003*	*0.017*	*0.003*	*0.005*	*0.003*

Note:

6.4.2 Risk Results – Non-Radiological

The following tables present the estimated non-radiological risk (SI) results for terrestrial receptors, based on their respective environmental media exposures and their corresponding benchmarks (see Section 6.3).

Tier 1

Tier 1 estimates are based on maximum concentrations in environmental media.

Table 6.20 presents Tier 1 Case 1 SI values for terrestrial receptors, whereas Table 6.21 presents Tier 1 SI values for aquatic receptors. Table 6.22 and Table 6.23 present Tier 1 Case 2 SIs for terrestrial and aquatic receptors, respectively.

Tier 2

Tier 2 dose assessment is performed for any COPC-receptor combinations with estimated doses that exceed the corresponding TRV in the Tier 1 assessment (i.e. benthic invertebrates). Table 6.24 presents Tier 2, Case 2 SI values for benthic invertebrates.

TIER 1: Case 1 (max. SW, regardless of location)

Table 6.20 EcoRA – Non-Radiological Risk Results – Terrestrial Receptors (Tier 1, Case 1)

COPC	American Robin	Cotton-Tail Rabbit	Earthworm (soil)	Great Horned Owl	Meadow Vole	Red Fox	Terr. Vegetation	Yellow Warbler	Earthworm (GW)
Uranium	0.17	0.015	0.009	0.003	0.007	0.015	0.009	0.048	0.12
TCE	NC	NC	NC	NC	NC	NC	NC	NC	NC
Cis-1,2-DCE	NC	NC	NC	NC	NC	NC	NC	NC	NC
Trans-1,2-DCE	NC	NC	NC	NC	NC	NC	NC	NC	NC
1,1-DCE	NC	NC	NC	NC	NC	NC	NC	NC	NC
Chloroethane	NC	NC	NC	NC	NC	NC	NC	NC	NC
Tetrachloroethylene	NC	NC	NC	NC	NC	NC	NC	NC	NC
1,1,1-Trichloroethane	NC	NC	NC	NC	NC	NC	NC	NC	NC
Vinyl Chloride	NC	NC	NC	NC	NC	NC	NC	NC	NC

NC - Not Calculated (TRVs or TFs not available).

Table 6.21 EcoRA – Non-Radiological Risk Results – Aquatic Receptors (Tier 1, Case 1)

COPC	Aq. Vegetation	Benthic Fish	Benthos	Horned Grebe	Lesser Scaup	Pelagic Fish
1,1-Dichloroethylene	NC	NC	NC	NC	NC	NC
Chloroethane	NC	NC	NC	NC	NC	NC
Tetrachloroethylene	0.005	0.005	0.005	NC	NC	0.005
cis-1,2-Dichloroethylene	NC	NC	NC	NC	NC	NC
trans-1,2-Dichloroethylene	NC	NC	NC	NC	NC	NC
Trichloroethylene	0.024	0.024	0.024	NC	NC	0.024
Uranium	0.001	0.004	0.23	0.002	0.006	0.011
Vinyl Chloride	NC	NC	NC	NC	NC	NC

NC - Not Calculated (TRVs or TFs not available).

TIER 1: Case 2 (max. SW, estimated in vicinity of municipal sewage outfall diffuser)

Table 6.22 EcoRA – Non-Radiological Risk Results – Terrestrial Receptors (Tier 1, Case 2)

COPC	American Robin	Cotton-Tail Rabbit	Earthworm (soil)	Great Horned Owl	Meadow Vole	Red Fox	Terr. Vegetation	Yellow Warbler	Earthworm (GW)*
Uranium	0.17	0.016	0.009	0.003	0.008	0.016	0.009	0.049	0.122

NC - Not Calculated (TRVs or TFs not available).
* Independent of Case; Case 1 results equal to Case 2 results.

Table 6.23 EcoRA – Non-Radiological Risk Results – Aquatic Receptors (Tier 1, Case 2)

COPC	Aq. Vegetation	Benthic Fish	Benthos	Horned Grebe	Lesser Scaup	Pelagic Fish
Uranium	0.009	0.034	**1.89**	0.014	0.044	0.093

NC - Not Calculated (TRVs or TFs not available).
Bold & Shaded – indicates where estimated dose exceeds corresponding ENEV.

TIER 2: Case 2 (max. SW, estimated in vicinity of municipal sewage outfall diffuser)

Table 6.24 EcoRA – Non-Radiological Risk Results – Aquatic Receptors (Tier 2, Case 2)

COPC	Benthos
Uranium	0.027

NC - Not Calculated.

6.4.3 Discussion of Risk Results

6.4.3.1 Radiological

As shown in Section 6.4.1, for all ecological receptors (terrestrial and aquatic), no radiological risk SIs were found to be greater than 1, and therefore, the estimated radiological doses to terrestrial receptors are less than the corresponding benchmark value. No undue effects are anticipated.

6.4.3.2 Non-Radiological

As shown in Section 6.4.2, for all aquatic and terrestrial receptors, only benthos showed screening index results greater than 1, for Tier 1, Case 2. As such, Tier 2 calculations were undertaken, using a dilution factor to account for dilution of CFM effluent in total STP effluent (see Section 3.4.1). Tier 2 calculations for benthos (Case 2) produced non-radiological SIs less than 1. Therefore, after Tier 2 calculations there is no residual risk, the estimated non-radiological doses for all ecological receptors are less than their corresponding benchmark values, and no undue effects are anticipated.

6.5 Uncertainties in the EcoRA

The main uncertainties in the EcoRA, and the assumptions made to address them, are outlined below.

Exposure Point Concentrations

Measured concentrations of COPCs, and measured activities of radionuclides, were used wherever such data was available. For non-radiological COPCs, the EcoRA uses two cases as described in Section 6.2.4: one relying on the maximum measured concentration among appropriate surface water monitoring locations; and the other relying on total measured uranium in facility effluent. For surface water monitoring data, the use of these concentrations assumes that receptors are exposed to these higher concentrations year-round when, in reality, there is both spatial and temporal variations in concentrations. Thus, exposures are likely overestimated. A similar assumption is made regarding the CFM effluent data: where it is assumed that the total amount of uranium is present for the entire exposure period, when in reality the amount of uranium will vary over time.

No uranium-series radionuclides (U-238, U-234, and U-235) are directly measured. Rather, measured uranium data for environmental media focus on natural uranium levels. Therefore, the activity concentrations of uranium-series radionuclides had to be estimated as outlined in Sections 0 and 5.2.2.2. Although for EcoRA this involves the use of specific activity estimates, these estimations use the maximum concentration (or total annual amount of uranium – for case 2) as their starting point. It is therefore unlikely that the resulting doses would be underestimated given the use of these concentrations.

Uncertainty is also acknowledged in concentration estimates derived using modelling methodologies (i.e. predicted offsite soil uranium levels, and vapour concentrations based on COPCs in soil or groundwater). This uncertainty is due to the nature of the various input parameters used, and the degree to which they are

correct, representative, and protective. To reduce uncertainty in modelling, site-specific input parameters where used wherever available – in particular for the soil accumulation modelling. Where site-specific data were not available, conservative default values were chosen; in this way the resulting estimates are unlikely to underestimate the concentrations of COPCs.

Receptor Occupancy & Home Ranges

All mobile receptors are assumed to be present for the entire year, despite any potential migratory behaviour. In addition, the home range of all mobile receptors is assumed to be limited to the location of these maximum concentrations, when in reality, several mobile receptors have large home ranges and the location of a maximum concentration might represent only a small portion of their overall range. Thus, exposures are likely to be conservatively overestimated.

Transfer Factors

Measured data from the site focus on environmental media and facility effluents, not tissue concentrations. Therefore, the concentrations/activities in biota had to be estimated using transfer factors from literature as well as food intake calculations. There is some uncertainty involved in the use of transfer factors and data that are not site-specific; however, in the absence of measured data, this approach provides the only method for estimating concentrations and for estimating transfer up the food chain.

Receptor Characterizations/Exposure Parameters

The characteristics of ecological receptors – mobile receptors in particular - represent another source of uncertainty since receptors will adjust and vary their diet and behavior according to the food and water sources available and regional conditions in general. The characteristics (e.g., body weight; food, water, and soil consumption rates, etc.) for all receptors were selected based on a review of available information in various credible literature sources. However for some (though not all) literature sources, these parameters are obtained from studies involving animals in captivity, and therefore may not be fully representative of free-range animals in the wild. An underestimate of exposure might result from this – for example, by assuming a body weight that is greater than for animals in the wild - but there are other conservative assumptions that may compensate (e.g. assuming 100% of intake of a COPC is absorbed by the body).

Toxicity Reference Values

The TRVs used in the assessment were obtained from reputable sources; nonetheless, they are always associated with uncertainty due to the extrapolation of testing on lab species (e.g., rats) to field conditions as well as to the ecological receptors considered in this assessment. Additionally, toxicity information for a COPC was used regardless of its form in the test procedure, even though this may not be the same form used in the assessment (e.g., an oxide form compared to a more soluble form). It is difficult to determine the effect of these assumptions.

Another area of uncertainty in the risk assessment is the effect of multiple COPC. When dealing with toxic chemicals, there is potential interaction with other chemicals that may be found at the same location. It is well established that synergism, potentiation, antagonism or additivity of toxic effects occurs in the environment. A detailed quantitative assessment of these interactions is beyond the scope of the present study, and, for many COPC-receptor combinations there is not an adequate base of toxicological evidence to examine these interactions. This may result in an underestimate of the risk for some COPC combinations.

Likely the largest source of uncertainty is the limited availability of TRV data for ecological receptors exposed to chlorinated organics. TRVs were obtained for TCE and PCE for fish, benthic invertebrates, and aquatic vegetation. However, this represents the extent of available data, and TRVs could not be found for mammals, birds, terrestrial vegetation, and terrestrial invertebrates.

Summary

Table 6.25 provides a summary of the uncertainties discussed above. It can be seen from the table that, in general, the approaches or assumptions used to overcome uncertainties are likely to lead to an over-estimate of exposures and thus the conclusions of the assessment would remain unchanged.

Table 6.25 EcoRA – Summary of Uncertainties

Uncertainty	Likely Leads to Overestimate	Possibly Leads to Underestimate	Neither Overestimate or Underestimate
Use of maximum concentrations (or total uranium for case 2) to characterize exposures	X		
Estimation of radionuclide activity concentrations for those radionuclides without measured data (i.e. use of specific activity and secular equilibrium, based on maximum (or total – for case 2) measured U_{nat})	X		
Use of transfer factors to estimate tissue concentrations	X		
Use of literature characteristics for ecological receptors			X
Neglecting migratory behaviour, and home range fraction (I.e. assuming *all* ingested food, water, and soil is from within the study area)	X		
Use of laboratory-derived TRVs for chronic exposure and effects (see Section 6.3.1)	X		
Synergism, potentiation, antagonism, additivity of toxic effects		X	
Lack of TRV/toxicity data for chlorinated organics for terrestrial biota	*Identified as a gap in available literature information*		

7.0 CONCLUSIONS AND RECOMMENDATIONS

7.1 Conclusions

7.1.1 HHRA Conclusions

Radiological HHRA:

The radiological human health risk component identified that all Tier 1 doses are below the dose limit, for all human receptors (on-site and offsite workers, and members of the public). Therefore, undue risk to human receptors from environmental radiation doses is unlikely.

Non-Radiological HHRA:

The non-radiological human health risk component identified one receptor-COPC combination with residual risk:

- **TCE & VC in *onsite* groundwater:** pertaining to the on-site subsurface worker receptor, and the combined 'resident & on-site subsurface worker' receptor.
- **VC in *offsite* groundwater:** pertaining to the off-site subsurface worker receptor.
- **Uranium in *onsite* indoor air:** pertaining to the on-site maintenance worker receptor.

For TCE and VC in onsite and offsite groundwater, the residual risks posed to subsurface contractor worker receptors are from oral and dermal exposure, which is easily and effectively mitigated through the implementation of specific health and safety procedures (and equipment) already in place at the site. The worker exposure portion is the same for the 'resident & onsite subsurface worker' receptor, and as such, the same facility health and safety measures apply.

For uranium in onsite indoor air, there are procedures at the facility requiring workers to wear respirators when performing specific job tasks in certain work areas and these procedures should also apply to any non-NEWs and contractors who perform maintenance-type activities at the facility.

7.1.2 EcoRA Conclusions

The radiological component of the EcoRA identified no screening index results with values greater than 1 for terrestrial or aquatic receptors, and therefore, the estimated radiological doses to all ecological receptors are less than the corresponding dose benchmarks. As a result, no undue effects are anticipated.

The non-radiological component of the EcoRA identified no screening index results with values greater than 1 for terrestrial or aquatic receptors for Case 1 (based on measured surface water concentration data). Tier 1 SI results for Case 2 showed a value greater than 1 only for benthos, and as a result, benthos was carried forward for Tier 2 calculations. Tier 2 (Case 2) calculations for benthos incorporated a dilution factor to account for dilution of CFM effluent by additional sewer effluent volumes as described in Section 3.4.1.

Tier 2 (Case 2) SI results were below 1, and therefore, there are no residual risk exceedances for any ecological receptors and no undue effects are anticipated.

7.2 Recommendations

The following recommendation is offered, based on the findings of this study:

- CFM should require all on-site non-Cameco workers or contractor (i.e. non-NEWs) to follow the same health and procedures with regard to the use of respirators while working inside the facility. Cameco may also consider a requirement for all on-site workers to be NEWs. This policy would ensure that workers are trained, protected and monitored effectively and on a harmonized basis.

8.0 QUALITY ASSURANCE AND QUALITY CONTROL

Arcadis has an internal Quality Management System that has been certified to ISO 9001:2008. The Arcadis QMS was applied to the ERA process. It includes (but is not limited) the following elements that are required under CSA N288.6 (Section 10.2):

i. Data gathering: Sources (either Cameco internal monitoring data, or external references) documented. Where possible, obtained data in Excel to minimize copy errors.

ii. Data management: Shared data folder to ensure all team members have access to the most up-to-date information. Summary of data and sources in report. Document and e-mail naming convention to optimize version tracking.

iii. Data analysis: Use of Quality-Assured (QA'ed) calculation models for HH Rad, Eco Rad, Eco NonRad. Use of QA'ed spreadsheet models for HH Rad. Screening was QA'ed.

iv. Report preparation: Use of tracked changes, OneDrive, etc. to manage multiple inputs.

v. Record keeping: Bi-weekly tracking (at a minimum) to ensure project progress. Management of team resources to ensure staff are available when required, e.g., for QA or modelling.

Much of the data used in this assessment comes from previous Arcadis (formerly SENES) studies that were already reviewed and accepted by CNSC. Internal peer review is performed for all major aspects of the risk assessment, as seen in Table 8.1 below.

Table 8.1 Internal Peer Review of ERA

Section	Prepared By	Reviewed By	Example Findings
HHRA: Radiological	[redacted]	[redacted]	Improvements made on receptor characteristics. Small correction made to specific activity calculation.
HHRA: Non-Radiological	[redacted]	[redacted]	Updated U TRV to reflect most recent reference document.
EcoRA: Radiological	[redacted]	[redacted]	Small typo corrected in rad concentration.
EcoRA: NonRadiological	[redacted]	[redacted]	Small typo corrected in reports.

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Arcadis Canada Inc.

121 Granton Drive, Suite 12

Richmond Hill, ON L4B 3N4

Tel 905.764.9389

Fax 905.764.9386

Arcadis.com