

Rook I Project

Environmental Impact Statement

TSD XV: Tailings Source Term Derivation Report

TAILINGS SOURCE TERM DERIVATION TECHNICAL SUPPORT DOCUMENT FOR THE ROOK I PROJECT

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Executive Summary

NexGen Energy Ltd. (NexGen) is proposing to develop a new uranium mining and milling operation in northwestern Saskatchewan, called the Rook I Project (Project). The Project would include an underground mine and surface facilities to support the extraction and processing of uranium ore from the Arrow deposit. This technical support document to the Environmental Impact Statement (EIS) details the methods and assumptions used to generate source term predictions for backfilled composite tailings and/or process wastes that will be disposed in the underground workings.

The source term derivation process included the development of conceptual models that represent the anticipated hydrological, geochemical, and radiological processes that will influence mass loading rates from tailings and process wastes disposed in the mine stopes and underground tailings management facility (UGTMF). Two solute mass transfer mechanisms are anticipated to occur post-closure when the workings are backfilled and the mine is flooded: advective mass transfer and diffusive mass transfer.

Source term models were developed for the primary stopes, secondary stopes, and UGTMF. The individual source terms consist of both advective and diffusive mass transfer components that are simulated using an engineering modelling approach. This approach is supported by a purposely designed characterization program with empirical laboratory measurements of key mass transfer processes.

Given the complexity of the physical and chemical processes that determine the magnitude and rate of advective and diffusive mass transfer from the underground mine stopes and UGTMF, simplifying assumptions were used in the source term models to reduce the necessary parameters and/or variables to those that can be measured using applicable laboratory tests. Additional bounding arguments were made to establish a conservative case for the mine stopes and UGTMF source terms that intentionally overestimate the mass loading from these disposal areas. Specifically, source terms were developed assuming that mass transfer rates of constituents from the tailings and process wastes are constant over time, and leaching rates and leachate qualities are equivalent to peak values measured during the laboratory measurements.

Key findings from the source term predictions for underground disposal of tailings and process wastes are:

- All tailings and process wastes produced from the Project will be mixed in various ratios on the surface to produce two types of composite materials: cemented paste backfill (CPB) and cemented paste tailings (CPT). These composite wastes consist of a combination of neutralized leached residue, process wastes, and cement binder. The CPB and CPT materials are characterized by a low hydraulic conductivity and primarily consist of acid-leach resistant minerals from the ore and gypsum. The materials are classified as non-potentially acid generating and have alkaline leachable fractions of solutes and radionuclides. The CPB will be disposed in the primary and secondary mine stopes and used for plugging and capping of the disposal chambers of the UGTMF. The CPT will be disposed in the UGTMF.
- Estimated porewater chemistries for the primary and secondary stopes are very similar, since CPB forms the dominant material type that will be disposed in these workings. Drainage chemistries for the UGTMF are different due to the inclusion of the process wastes and lower binder contents.
- Estimated porewater chemistries for the underground mine stopes and UGTMF are generally characterized by highly alkaline drainage (i.e., pH greater than 10), sulphate-calcium-sodium dominated ion composition, and elevated metals and radionuclides.

- Alkalinity and pH are predicted to be higher for the underground mine stopes compared to the UGTMF. This relationship is due to the higher binder content needed for the high-strength CPB in the stopes, compared to the lower strength CPT that will be used to backfill the UGTMF.
- Elevated metal concentrations for the underground mine stopes and UGTMF are noted for aluminum, arsenic, cadmium, chromium, copper, iron, lead, molybdenum, selenium, silver, uranium, and zinc. These metals are elevated due to their presence in the neutralized leached residue and process wastes, as well as their solubility under alkaline drainage conditions. The estimated concentrations are higher in the UGTMF compared to the primary and secondary stopes, except for aluminum, molybdenum, and selenium. The highest concentrations for aluminum, molybdenum, and selenium are estimated for the upper cases of the primary and secondary stopes, which are characterized by the highest alkalinity and pH values.
- Elevated concentrations of radium-226 are predicted in the estimated drainage chemistry for the backfilled stopes and UGTMF. Estimated concentrations for lead-210, polonium-210, radium-226, and radium-228 are slightly higher in the primary and secondary stope source terms compared to the UGTMF source terms.
- Estimated diffusivity values are similar for primary and secondary stopes since CPB forms the dominant material type that will be disposed in these mine workings. Observed diffusivity values for the UGTMF are generally much higher due to the inclusion of the process wastes and lower binder contents. One exception to this observation is uranium, which has a higher observed diffusivity for the primary and secondary stopes
- The highest observed diffusivity values are estimated for aluminum, antimony, barium, beryllium, iron, lead, magnesium, manganese, mercury, nitrate, nitrite, phosphate, polonium-210, radium-226, tin, uranium, vanadium, and zinc. In the case of aluminum, antimony, beryllium, cadmium, copper, iron, manganese, radium-226, tin, and zinc, the observed diffusivity values are more than two orders of magnitude higher in the UGTMF compared to those of the primary and secondary stopes.
- Validation of the source term predictions is not possible due to a lack of suitable analogue sites or publicly available analogue data. As a result, the source terms were developed to be conservative to account for input uncertainties. It is expected that the source terms will be further refined and modified as additional characterization, testing, and monitoring data become available.

The underground mine stopes and UGTMF source terms were incorporated in the groundwater solute transport model for the Project. The groundwater solute model simulates the flow of groundwater around and through the mine stopes and UGTMF and, combined with the source terms, calculates the mass loading from the tailings materials to the groundwater system to support the effects assessment for hydrogeology (EIS Section 8, Hydrogeology).

Abbreviations and Units of Measure

Abbreviation	Definition
CPB	cemented paste backfill
CPT	cemented paste tailings
EIS	Environmental Impact Statement
Golder	Golder Associates Ltd.
LEAF	Leaching Environmental Assessment Framework
MTP	modified triaxial permeability
NexGen	NexGen Energy Ltd.
OPC	ordinary Portland cement
Project	Rook I Project
SFE	shake flask extraction
U ₃ O ₈	triuranium octoxide
UGTMF	underground tailings management facility

Unit	Definition
%	percent
°C	degrees Celsius
Bq/g	becquerels per gram
Bq/L	becquerels per litre
d	day
kg/m ³ dw	kilograms per cubic metre dry weight
km	kilometre
L	litre
m	metre
m ²	square metre
m/s	metres per second
m ² /s	square metres per second
m ³	cubic metre
mg/kg	milligrams per kilogram
mg/L	milligrams per litre
mg/m ² /s	milligrams per square metre per second
MPa	megapascal
pH	potential of hydrogen; measure of the acidity or alkalinity of a solution on a scale of 0 to 14
s	second
wt. %	weight percent

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1 INTRODUCTION

NexGen Energy Ltd. (NexGen) is proposing to develop a new uranium mining and milling operation in northwestern Saskatchewan, called the Rook I Project (Project). The Project would be located approximately 40 km east of the Saskatchewan-Alberta border, 130 km north of the town of La Loche, and 640 km northwest of the city of Saskatoon (Figure 1-1). The Project would reside within Treaty 8 territory and the Métis Homeland. At a regional scale, the Project would be situated within the southern Athabasca Basin adjacent to Patterson Lake, along the upper Clearwater River system. Patterson Lake is at the interface of the Boreal Shield and Boreal Plain ecozones. Access to the Project would be from an existing road off Highway 955 (Figure 1-2), with on-site worker accommodation serviced by fly-in/fly-out access.

The Project would include the following key facilities to support the extraction and processing of uranium from the Arrow deposit for transportation off site (Figure 1-3):

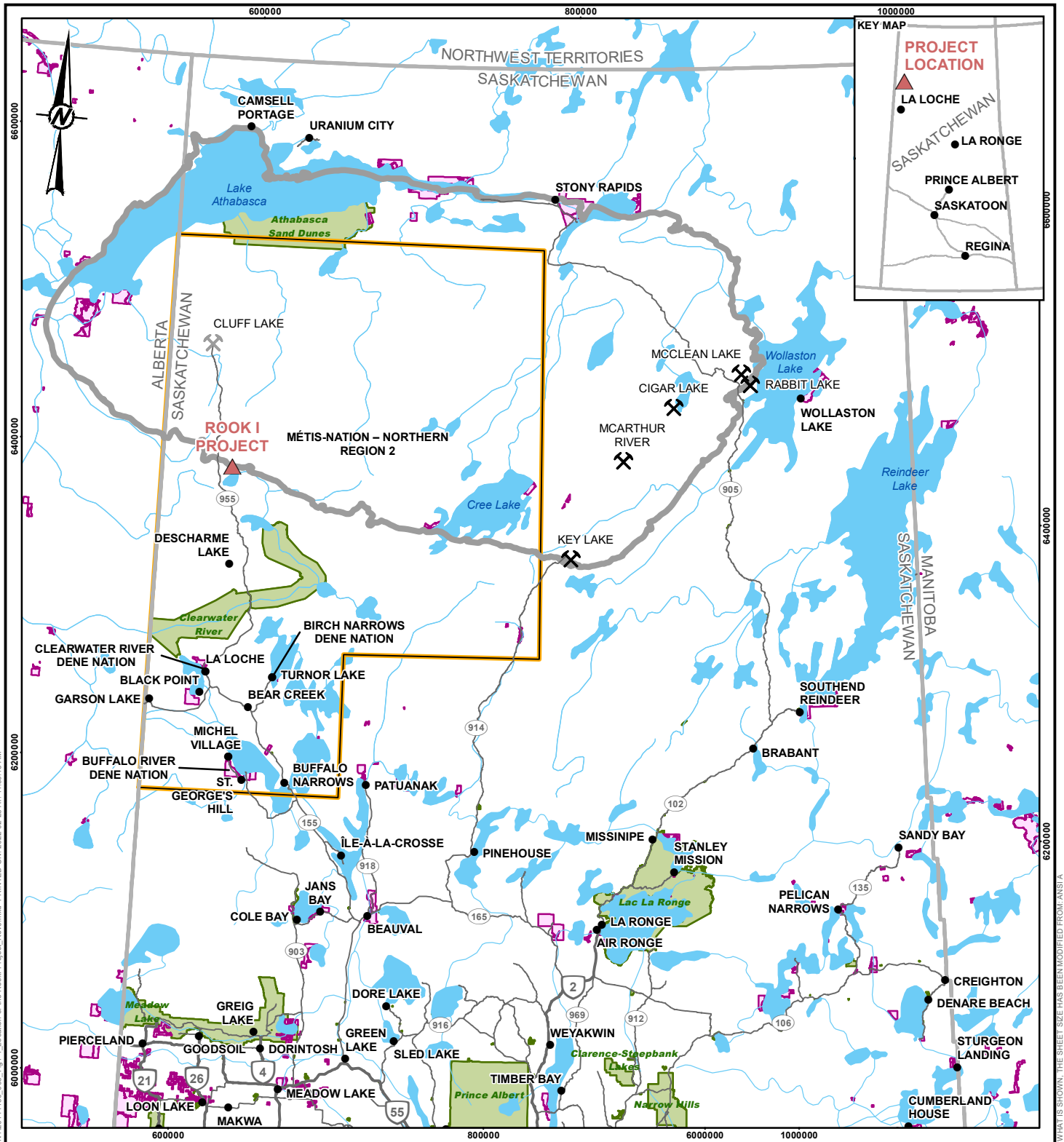
- underground mine development;
- process plant buildings, including uranium concentrate packaging facilities;
- paste tailings distribution system;
- underground tailings management facility (UGTMF);
- potentially acid generating waste rock storage area;
- non-potentially acid generating waste rock storage area;
- special waste rock¹ and ore storage stockpiles;
- surface and underground water management infrastructure, including water management ponds, effluent treatment plant, and sewage treatment plant;
- conventional waste management facilities and fuel storage facilities;
- ancillary infrastructure, including maintenance shop, warehouse, administration building, and camp;
- airstrip and associated infrastructure; and
- access road to Project and site roads.

Predicted water qualities or solute mass loadings, also referred to as source terms, were developed for the underground disposal of tailings (neutralized leach residue) and process wastes (gypsum precipitates and effluent precipitates) at the Project site. This technical support document to the Environmental Impact Statement (EIS) details the source term development for the underground mine workings, which include the mine stopes (primary and secondary stopes) and UGTMF. This document includes a description of the backfilled composite tailings and/or process wastes that will be disposed underground, the source term development framework (i.e., the approach, inputs, assumptions, and methods), and results. The geotechnical, geochemical, and radiological properties of the tailings, process waste, binder, and composite materials that form the basis of the

¹ Special waste rock is mine rock that is mineralized with insufficient grade to be considered ore (i.e., greater than 0.03% of triuranium oxide [U_3O_8] and less than 0.26% U_3O_8). All special waste would be temporarily stored in the special waste rock stockpile.

source term calculations, are reported in a Technical Support Document (TSD) XVI Tailings Geochemical Characterization Report and should be read in conjunction with this report.

The underground mine stopes and UGTMF source terms were incorporated in the groundwater solute transport model for the Project and support the effects assessment for hydrogeology (EIS Section 8, Hydrogeology).

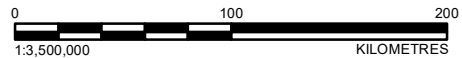


LEGEND

- POPULATED PLACE
- ⌘ URANIUM MINING FACILITY (ACTIVE)
- ⌘ URANIUM MINING FACILITY (DECOMMISSIONED)
- PRIMARY HIGHWAY
- SECONDARY HIGHWAY
- WATERCOURSE
- ▭ ATHABASCA BASIN BOUNDARY
- ▭ INDIAN RESERVE
- ▭ PROVINCIAL PARKS
- ▭ WATERBODY
- ▲ PROJECT LOCATION
- ▭ MÉTIS NATION-SASKATCHEWAN NORTHERN REGION 2

REFERENCE(S)

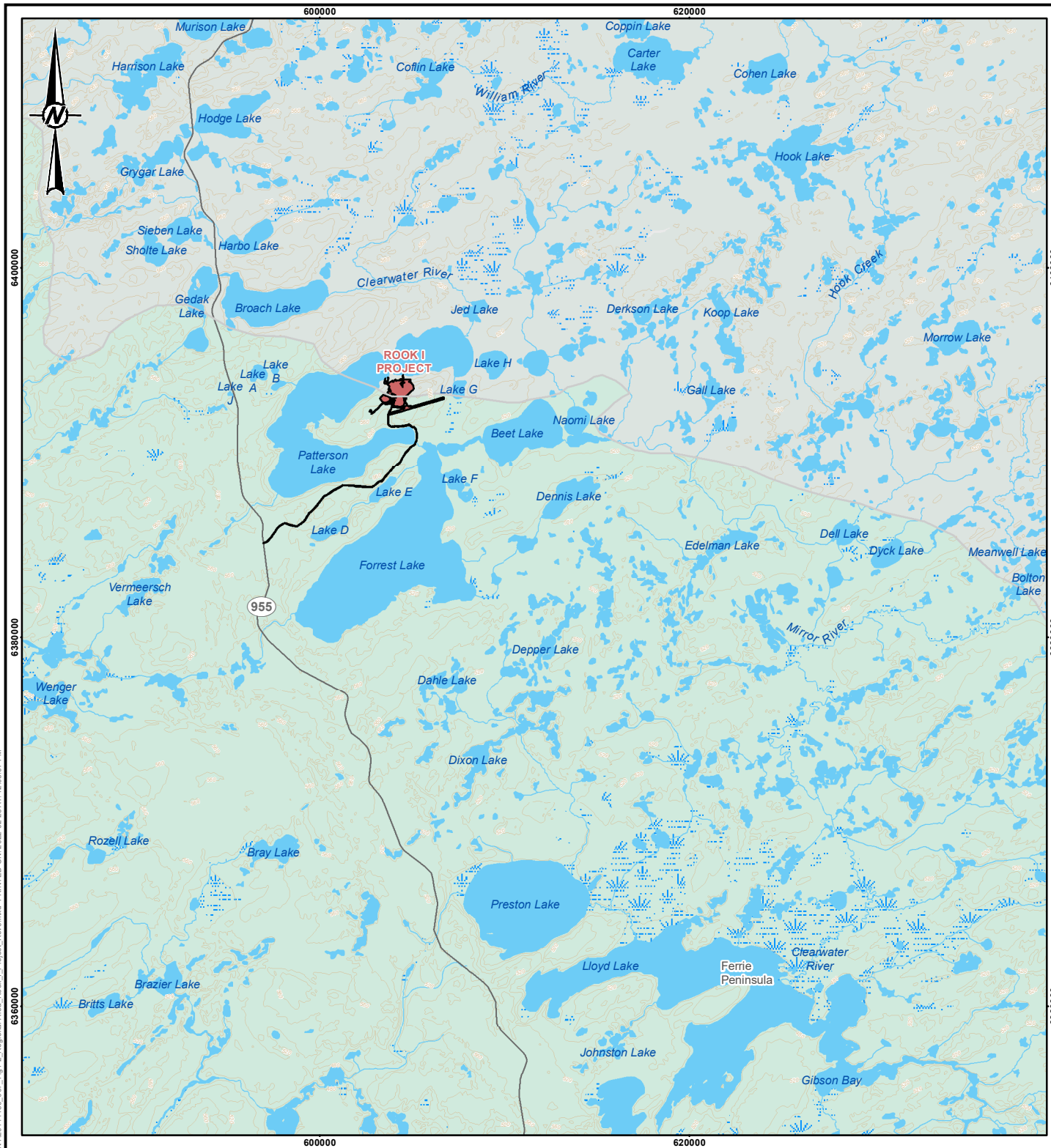
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 2. PARKS OBTAINED FROM IHS MARKET CANADA ULC.
- PROJECTION: UTM ZONE 12 DATUM: NAD 83



ROOK I PROJECT			
LOCATION OF THE ROOK I PROJECT			
CONSULTANT	PROJECT 20144150	PHASE 3314 - 6	
	DESIGN JMC 2022-02-28	SCALE AS SHOWN	REV. 0
	GIS NO 2022-02-28	FIGURE 1-1	
	CHECK JMC 2022-02-28		
	REVIEW MM 2022-02-28		

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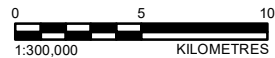


LEGEND

- ELEVATION CONTOUR (20 m INTERVAL)
- SECONDARY HIGHWAY
- WATERCOURSE
- ATHABASCA BASIN
- WATERBODY
- WETLAND
- WOODED AREA
- PROPOSED PROJECT FOOTPRINT

REFERENCE(S)

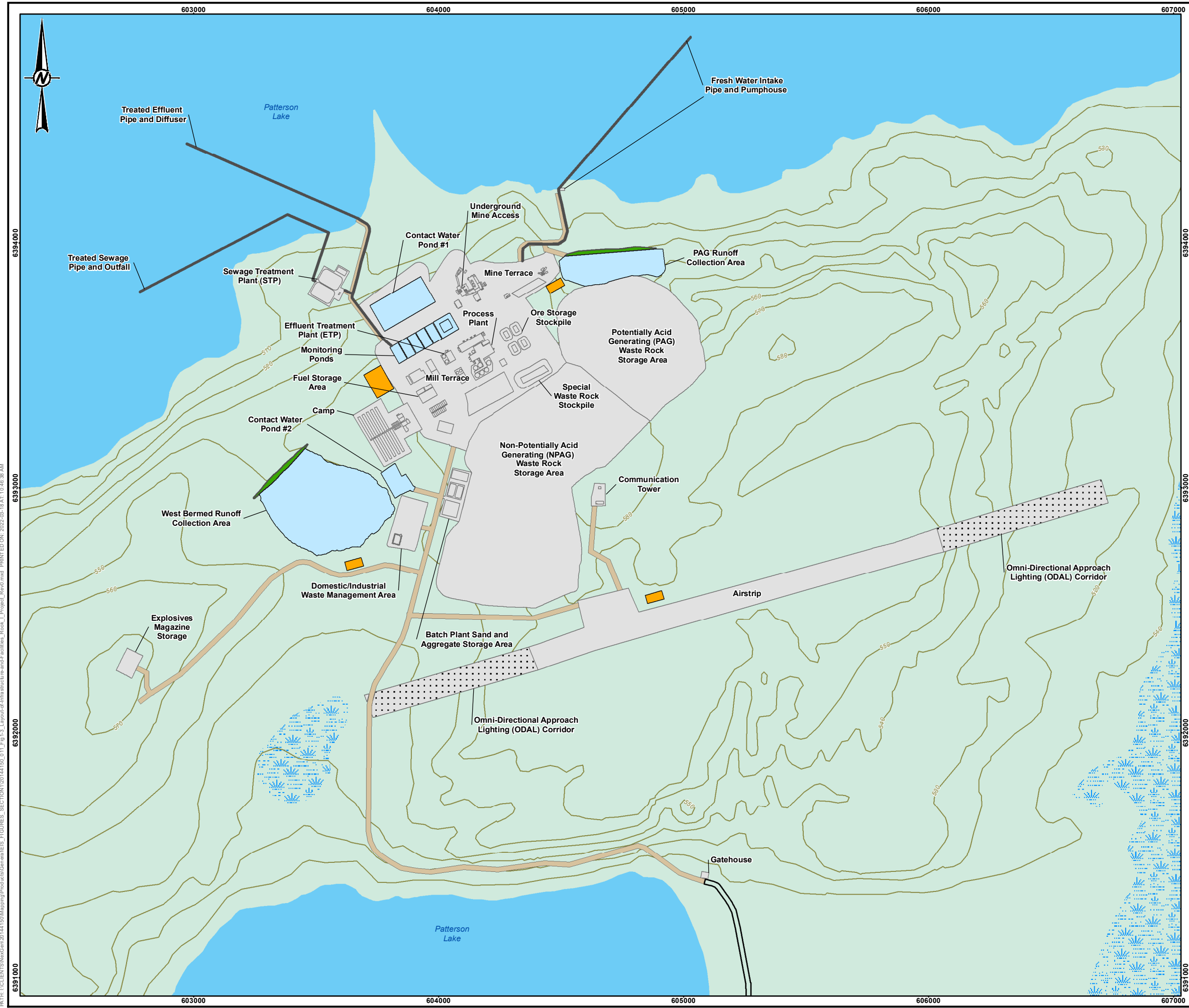
1. PROJECT FEATURES OBTAINED FROM NEXGEN, APRIL 6, 2021.
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- PROJECTION: UTM ZONE 12 DATUM: NAD 83



PROJECT		20144150		PHASE		3314 - 6	
DESIGN		JMC	2022-02-28	SCALE AS SHOWN		REV. 0	
GIS		NO	2022-02-28	FIGURE 1-2			
CHECK		JMC	2022-02-28				
REVIEW		MM	2022-02-28				
PROJECT		NexGen Energy Ltd. ROOK I PROJECT					
TITLE							
REGIONAL AREA OF THE ROOK I PROJECT							
CONSULTANT		GOLDER MEMBER OF WSP					

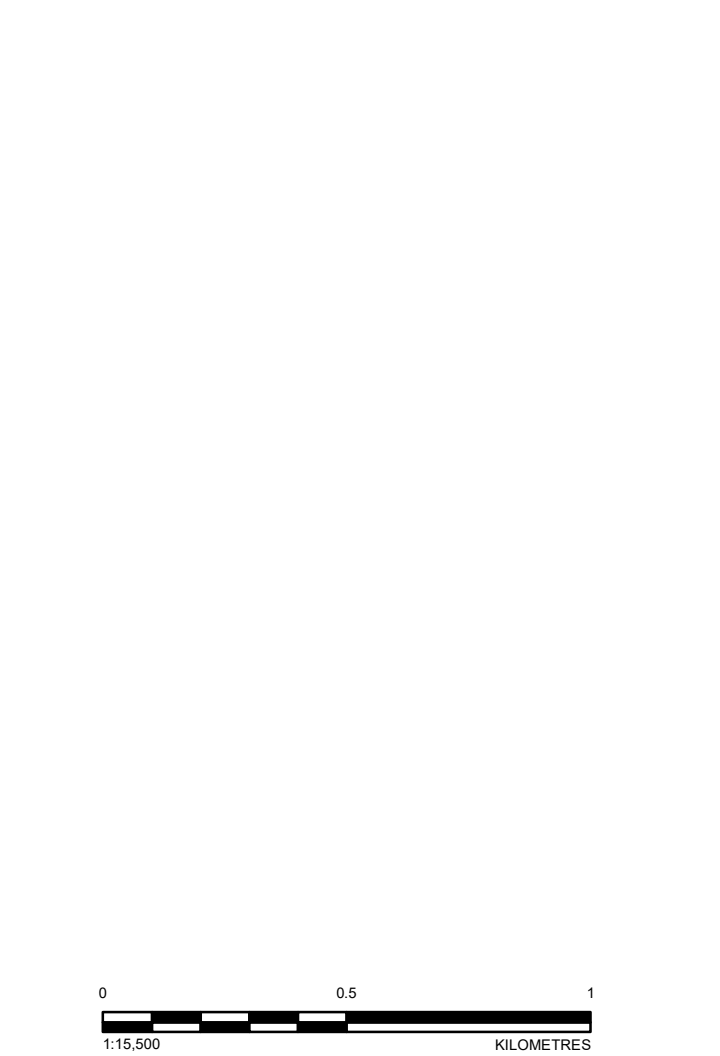
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LEGEND

- ELEVATION CONTOUR (10 m INTERVAL)
- WATERBODY
- WETLAND
- WOODED AREA
- INTAKE OR DISCHARGE PIPE
- ACCESS ROAD
- CONTACT WATER CONTAINMENT BERM
- OMNI-DIRECTIONAL APPROACH LIGHTING (ODAL) CORRIDOR
- PROJECT INFRASTRUCTURE
- SITE ROAD
- TOPSOIL STORAGE AREA
- WATER MANAGEMENT POND



REFERENCE(S)
 1. PROJECT FEATURES OBTAINED FROM NEXGEN, APRIL 6, 2021 AND UPDATED JUNE 8, 2021 .
 2. BASE DATA OBTAINED FROM GEOGRATIS, © DEPARTMENT OF NATURAL RESOURCES CANADA. ALL RIGHTS RESERVED.
 PROJECTION: UTM ZONE 12 DATUM: NAD 83

ROOK I PROJECT				
LAYOUT OF INFRASTRUCTURE AND FACILITIES FOR THE ROOK I PROJECT				
<table border="1" style="width: 100%; border-collapse: collapse;"> <tr> <td style="text-align: center;"> GOLDER <small>MEMBER OF WSP</small></td> <td style="font-size: 0.8em;"> PROJECT 20144150 DESIGN JV 2020-03-13 GIS NO 2022-03-18 CHECK JMC 2022-03-18 REVIEW MM 2022-03-18 </td> <td style="font-size: 0.8em;"> PHASE 3314 - 6 SCALE AS SHOWN REV. 0 </td> </tr> </table>	GOLDER <small>MEMBER OF WSP</small>	PROJECT 20144150 DESIGN JV 2020-03-13 GIS NO 2022-03-18 CHECK JMC 2022-03-18 REVIEW MM 2022-03-18	PHASE 3314 - 6 SCALE AS SHOWN REV. 0	FIGURE 1-3
GOLDER <small>MEMBER OF WSP</small>	PROJECT 20144150 DESIGN JV 2020-03-13 GIS NO 2022-03-18 CHECK JMC 2022-03-18 REVIEW MM 2022-03-18	PHASE 3314 - 6 SCALE AS SHOWN REV. 0		

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1.1 Study Objectives

The study objective was to develop source terms for the mine stopes and UGTMF that estimate short-term (i.e., Operations) and longer-term (i.e., post-closure) mass loadings and water qualities from the backfilled composite tailings and process wastes.

The estimated source terms are incorporated in the groundwater solute transport model (EIS Section 8) to evaluate the combined mass loading effects from waste products associated with the Project (i.e., tailings and waste rock) to downgradient surface water receptors (EIS Section 10, Surface Water Quality and Sediment Quality).

1.2 Scope of Work

Geochemical source terms were derived for three underground disposal areas that will host backfilled composite tailings and/or process wastes produced from the Project. These underground disposal areas include primary mine stopes, secondary mine stopes, and the proposed UGTMF. The following approach was followed in the development of the source terms:

- 1) Develop conceptual models for geochemical and radiological processes that will influence mass loading rates from backfilled composite tailings and/or process wastes in the mine stopes and UGTMF.
- 2) Develop source term models for the mine stopes and UGTMF using simplifying assumptions and bounding arguments.
- 3) Derive source term estimates for the mine stopes and UGTMF using geotechnical, geochemical, and radiological data from the tailings and process waste characterization program.

2 BACKGROUND INFORMATION

2.1 Tailings and Process Waste Disposal

All tailings and process wastes produced from the Project during Operations will be mixed in the paste plant in specified ratios and disposed in the underground workings (NexGen 2021a). Two types of composite materials will be generated from the paste plant: cemented paste backfill (CPB) and cemented paste tailings (CPT). The CPB will consist of neutralized leach residue, water, and binder that are mixed in various ratios to meet strength requirements for disposal in the primary and secondary mine stopes and UGTMF. The CPT will consist of a mixture of neutralized leach residue, gypsum precipitate, effluent precipitate, and binder for disposal in the UGTMF. The binder to create the CPB is planned to consist of a 1:1 ratio of ordinary Portland cement (OPC) and slag, whereas the binder to create the CPT is planned to consist entirely of OPC. The CPB and CPT will be pumped from the paste plant to the underground via boreholes drilled during the initial years of mine production. The CPB and CPT disposal locations and associated strength requirements are summarized in Table 2-1.

A combination of transverse and longitudinal longhole stoping will be used to extract the uranium ore, and the transverse stoping will be completed using primary and secondary stopes (NexGen 2021a). An average transverse stope will be 12 metres (m) wide by 12 m long by 30 m high and an average longitudinal stope will be 24 m long by 5 m wide by 30 m high. Once extraction is complete, the mining stopes will be filled with CPB at a planned rate of 40 to 60 dry tonnes per hour. The mine plan also indicates that sill pillars will occur between the 500 to 530 Levels and 620 to 650 Levels (NexGen 2021a). Once these sill pillars are recovered, they will be

backfilled with CPB. The secondary stopes may be filled with CPT in the event that UGTMF chambers are not available for deposition.

The transverse approach will also be applied to the UGTMF, and CPT is planned to be deposited in the UGTMF chambers at a rate of 28 to 55 dry tonnes per hour (NexGen 2021a). The UGTMF is proposed to consist of 97 chambers that are 25 m wide by 25 m long by 60 m high. A new chamber will not be constructed until the adjacent chamber is backfilled and cured to maintain stability. An approximate 15 m wide pillar will separate each chamber (NexGen 2021a). A CPB plug will be placed at the base of the chamber and a CPB cap will be placed within the upper 2 m with the purpose of preventing seepage during the curing process. It is assumed that the UGTMF will be composed of 85 percent (%) CPT-filled chambers and 15% CPB-filled caps and plugs. The UGTMF chambers may be filled with CPB when mining stopes are not available for deposition. The general layout of the UGTMF feasibility study design is provided in Figure 2-1.

Table 2-1: Cemented Paste Backfill and Cemented Paste Tailings Disposal Locations and Strength Requirements

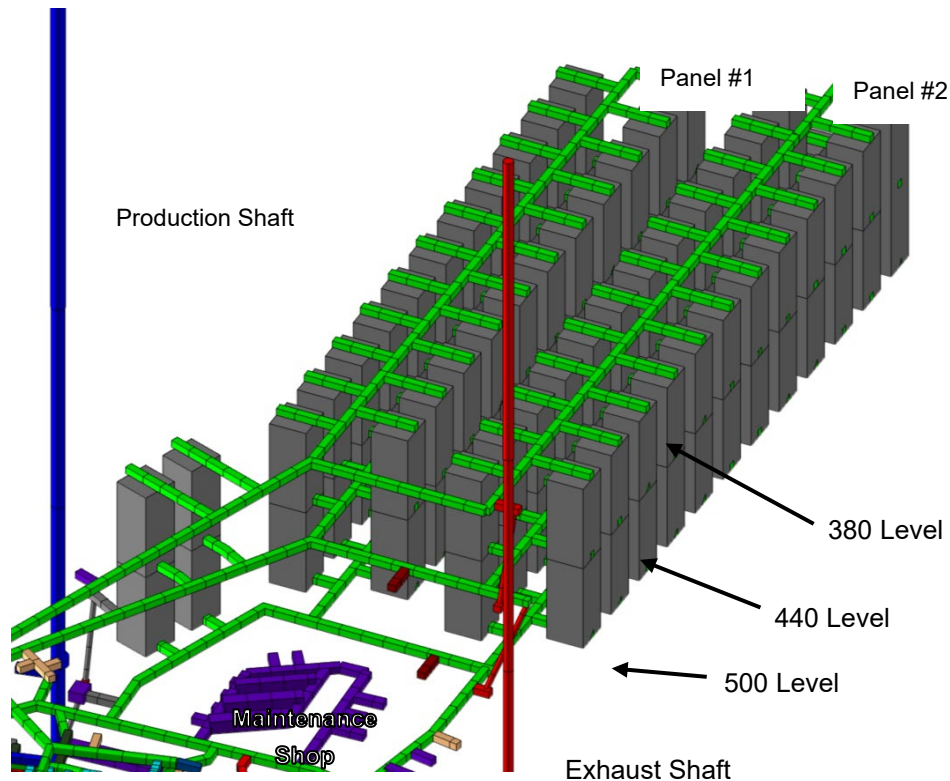
Underground Working		Target Strength (MPa)	Backfill Material
Primary stope		1.0	CPB
Secondary stope		0.5	CPB (and CPT during upset conditions ^(a))
Sill pillar		1.5	CPB
UGTMF	Cap and plug	1.5	CPB
	Chamber	0.2	CPT (and CPB during upset conditions ^(a))

Source: NexGen 2021a.

a) At the time of source term development, upset conditions were assumed to occur for 10% of Operations.

CPB = cemented paste backfill; CPT = cemented paste tailings; UGTMF = underground tailings management facility; MPa = megapascal.

Figure 2-1: Isometric View of the Underground Tailings Management Facility Feasibility Study Design



Source: NexGen 2021b.

2.2 Tailings and Process Waste Characterization

An ongoing tailings, process waste, binder, and composite material characterization program is being conducted under the direction of NexGen in support of the EIS and feasibility assessment. The characterization program began in 2019 and is focused on the geotechnical, geochemical, and radiological properties of backfilled composite tailings and process wastes that will be disposed underground. The characterization program evolved with the planning and design of the Project over this period and focused on the tailings and process wastes that were most representative of the selected waste disposal strategy and facility designs. The characterization program and its results to the end of 2020 are reported in TSD XVI.

The analytical data from the characterization program provide the basic material properties for the mine stopes and UGTMF source term derivation. It is noted that CPB and CPT are waste streams that will be composed of varying proportions of the representative composite samples from the characterization program. Of the composite materials developed for the geochemical characterization program, HHC-S and HLC-S were chosen to best represent CPB; HPLC, HPHC, HHGPLC, and HHGPHC were chosen to best represent CPT (Table 2-2). These samples were chosen to best represent the envelope of strength requirements and geochemical characteristics for the disposal of CPB and CPT in the underground workings. The material recipes for the representative samples from the characterization program are summarized in Table 2-3 (TSD XVI) and are the same material recipes that underpin the paste plant design. These cemented materials were cured for 28 days. Table 2-4 summarizes whether the analytical tests were conducted on competent or crushed samples.

Table 2-2: Characterization Program Samples Chosen to be Representative of Cemented Paste Backfill and Cemented Paste Tailings

Backfill Material	Representative Samples from Characterization Program	Description	Rationale
CPB	HHC-S	High-grade neutralized leach residue with a <u>high</u> OPC/slag binder content	Includes materials from the characterization program that were created using representative CPB components (i.e., neutralized leach residue and OPC/slag binder)
	HLC-S	High-grade neutralized leach residue with a <u>low</u> OPC/slag binder content	
CPT	HPLC	High-grade neutralized leach residue and effluent precipitates with a <u>low</u> OPC binder content	Includes materials from the characterization program that were created using representative CPT components (i.e., neutralized leach residue, process wastes, and OPC binder)
	HPHC	High-grade neutralized leach residue and effluent precipitates with a <u>high</u> OPC binder content	
	HHGPLC	High-grade neutralized leach residue, high-uranium gypsum precipitates and effluent precipitates with a <u>low</u> OPC binder content	
	HHGPHC	High-grade neutralized leach residue, high-uranium gypsum precipitates and effluent precipitates with a <u>high</u> OPC binder content	

CPB = cemented paste backfill; CPT = cemented paste tailings; OPC = ordinary Portland cement.

Table 2-3: Composition of Materials Chosen to Represent Cemented Paste Backfill and Cemented Paste Tailings

Backfill Material	Representative Samples from Characterization Program ^(a)	High-Grade Neutralized Leach Residue (%)	Gypsum (%)	Precipitates (%)	OPC (%)	Slag (%)	Water (%)
CPB	HLC-S	57.5	0	0	1.25	1.25	40
	HHC-S	44	0	0	8	8	40
CPT	HPLC	41	0	16.5	2.5	0	40
	HPHC	31.4	0	12.6	16	0	40
	HHGPLC	30.9	14.2	12.4	2.5	0	40
	HHGPHC	23.7	10.9	9.5	16	0	40

Source: TSD XVI.

a) Composite sample definitions are provided in Table 2-2.

CPB = cemented paste backfill; CPT = cemented paste tailings; OPC = ordinary Portland cement.

Table 2-4: Sample Type Used for Analytical Testing for All Cemented Paste Backfill and Cemented Paste Tailings Materials

Test	Competent Sample	Crushed Sample
Moisture Content	✓	-
Triaxial Permeability Test	✓	-
Mineralogy	-	✓
Acid Base Accounting	-	✓
Bulk Metals	-	✓
Whole Rock Oxides	-	✓

Table 2-4: Sample Type Used for Analytical Testing for All Cemented Paste Backfill and Cemented Paste Tailings Materials

Test	Competent Sample	Crushed Sample
Shake Flask Extraction	-	✓
Modified Triaxial Permeability Test	✓	-
Leaching Environmental Assessment Framework Test	✓	-

✓ = sample type used; - = sample type not used.

2.2.1 Cemented Paste Backfill Characteristics

Geotechnical, geochemical, and radiological properties of representative CPB materials are detailed in TSD XVI. A summary of the key characteristics of representative CPB materials is provided below and selected average results from the characterization program are summarized in Table 2-5.

- The hydraulic conductivity of CPB materials is influenced by the amount of binder in the material and ranges from the order of 10^{-08} metres per second (m/s) in the case of low binder variants to 10^{-10} metres per second (m/s) in the case of the high binder variants. A detailed summary of the hydraulic conductivity properties of the bedrock surrounding the stopes and UGTMF is described in Section 8 (Subsection 8.3.4). Hydraulic conductivity estimates in the bedrock can range from the order of 10^{-11} to 10^{-06} m/s, depending on the geological unit.
- The CPB materials are primarily composed of acid-leach resistant minerals (chamosite, kaolinite, muscovite, and quartz) that make up 96 weight percent (wt.%) to 100 wt.% of the solid component of the material. The low binder variants contain a small proportion of gypsum (2 wt.% to 4 wt.%). No carbonate or cementitious minerals were detected.
- Average total sulphur content of the representative CPB materials ranges from 0.85 wt.% to 0.95 wt.% and is dominated by sulphate. All CPB samples contain a neutralization potential ratio (NPR) greater than 2 and are classified as NPAG. The neutralization potential increases with higher binder content.
- The CPB materials contain enriched solid-phase concentrations of arsenic, bismuth, lead, molybdenum, selenium, silver, sulphur, and uranium. Constituents with a high leachability potential for representative CPB materials identified from the short-term leach testing include aluminum, antimony, chloride, cadmium, iron, molybdenum, selenium, sulphate, lead-210, and radium-226. The high sulphate leachability potential in the CPB materials is likely sourced from the process water that comprises 40% of the material.
- The lower binder variant of the CPB materials contained the highest average radioactivity (i.e., gross alpha activity 4,825 becquerels per gram [Bq/g] and gross beta activity 1,500 Bq/g) compared to the higher binder variant (i.e., gross alpha activity 2,900 Bq/g and gross beta activity 1,020 Bq/g). Radioactivity and radiochemical speciation analysis indicate that some radioactivity is mobilized during short-term leach testing with gross alpha activity of 105 to 148 becquerels per litre (Bq/L) and gross beta activity of 43 Bq/L to 53 Bq/L in the shake flask extraction (SFE) leachate. Radionuclide species with the highest leachable concentrations in CPB leachates were radium-226 (i.e., 48 Bq/L to 64 Bq/L) and lead-210 (i.e., 2.0 Bq/L to 17 Bq/L).

- Elemental liberation rates from CPB materials under advective mass transfer conditions indicate that the initial porewater quality is alkaline (i.e., potential of hydrogen [pH] 9.4 to 11) and remains alkaline (i.e., pH 10) after 10 pore volume replacements (Figure 2-2). All metal liberation rates, except for barium, are indicated to follow ordered rate kinetics (i.e., flushing) with the highest concentrations recorded in the first two pore volume replacements and decrease by an order of magnitude at five pore volume replacements (Figure 2-3). Recorded barium liberation rates indicate a slightly increasing trend in concentrations suggesting potential mineral (i.e., primary and secondary) controls.
- Diffusive mass flux values for representative CPB materials are greatest during the initial leaching period and most constituents follow ordered rate kinetics (i.e., flushing). Mass flux values are influenced by the percentage of binder in the sample and lower binder (i.e., or lower strength) variants generally exhibit greater diffusive mass flux values compared to higher binder variants (Figure 2-4).

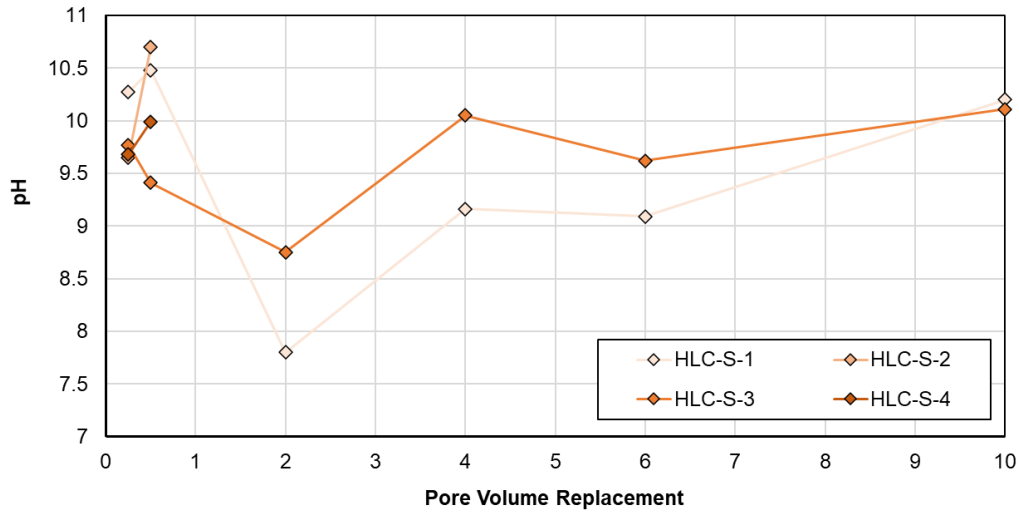
Table 2-5: Selected Average Geotechnical, Geochemical, and Radiological Properties of Representative Cemented Paste Backfill Materials

Characteristic	Parameter	Units	HLC-S ^(a)	HHC-S ^(a)
Geotechnical	Hydraulic conductivity	m/s	4.4×10^{-08}	3.5×10^{-10}
	Porosity	ratio	0.65	0.61
Geochemical (SFE)	pH	pH units	10	12
	Sulphate	mg/L	3,075	543
	Uranium	mg/L	0.0020	0.033
Geochemical (MTP first pore volume)	pH	pH units	10	n/a
	Aluminum	mg/L	0.53	n/a
	Uranium	mg/L	0.0056	n/a
Geochemical (LEAF mass flux – first three leach events)	Sulphate	mg/m ² /s	0.38	0.18
	Uranium	mg/m ² /s	0.000070	0.000063
Radiological (SFE)	Lead-210	Bq/L	2.0	17
	Radium-226	Bq/L	64	48

a) Composite sample definitions are provided in Table 2-2.

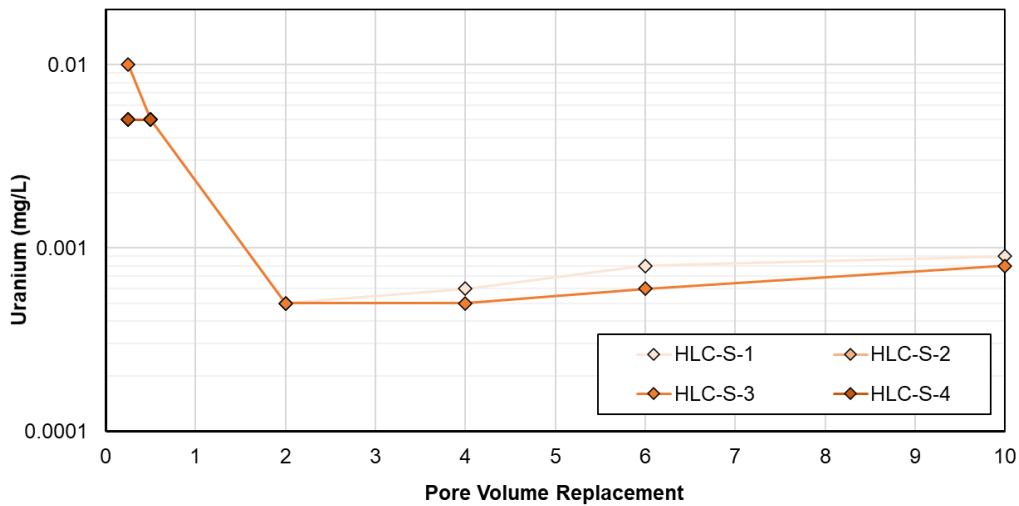
n/a = not applicable; MTP = modified triaxial permeability; LEAF = Leaching Environmental Assessment Framework; Bq/L = becquerels per litre; SFE = shake flask extraction.

Figure 2-2: pH versus Pore Volume Replacement for Low Binder Cemented Paste Backfill Material



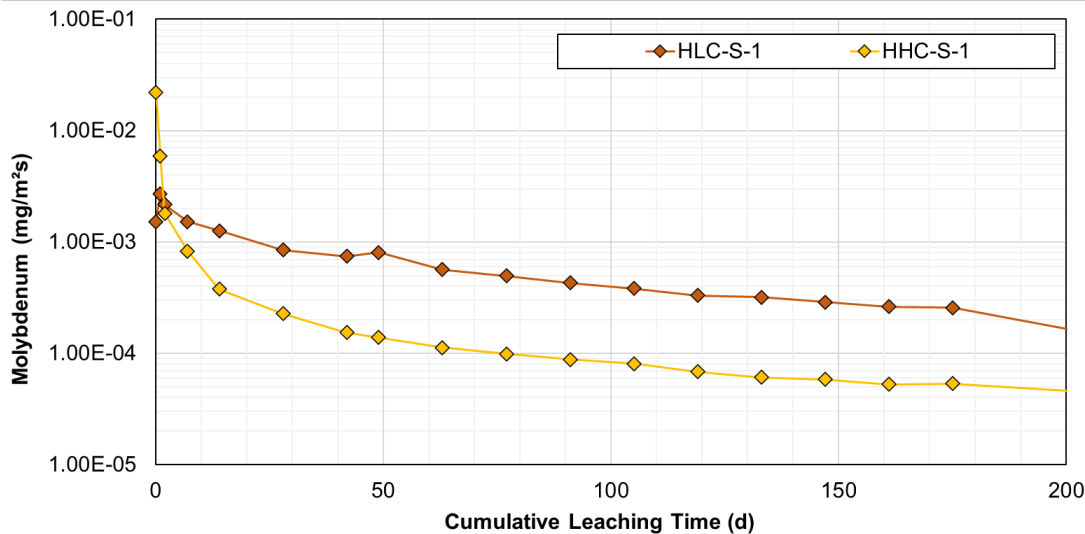
Note: Composite sample definitions are provided in Table 2-2.

Figure 2-3: Uranium Concentration versus Pore Volume Replacement for Low Binder Cemented Paste Backfill Material



Note: Composite sample definitions are provided in Table 2-2.

Figure 2-4: Mass Flux versus Cumulative Leaching Time for Representative Cemented Paste Backfill Materials



Note: Composite sample definitions are provided in Table 2-2.

2.2.2 Cemented Paste Tailings Characteristics

Geotechnical, geochemical, and radiological properties of representative CPT materials are detailed in TSD XVI. A summary of the key characteristics is provided below and selected average results from the characterization program are summarized in Table 2-6.

- The hydraulic conductivity of CPT is influenced by the amount of binder in the material and ranges from 10^{-08} m/s to 10^{-10} m/s. A detailed summary of the hydraulic conductivity properties of the bedrock surrounding the stopes and UGTMF is described in Section 8 (Subsection 8.3.4). Hydraulic conductivity estimates in the bedrock can range from the order of 10^{-11} to 10^{-06} m/s, depending on the geological unit.
- Representative CPT materials are primarily composed of acid-leach resistant minerals (i.e., clinocllore, muscovite, and gypsum) that make up 39 wt.% to 74 wt.% of the solid component of the material. The CPT materials also contain a relatively high proportion of gypsum (i.e., 9 wt.% to 54 wt.%). Carbonate (i.e., calcite) and cementitious (i.e., ettringite) minerals are also detected, likely due to the presence of the gypsum and effluent precipitates and a higher percentage of OPC binder. Detected calcite content ranges from 0 wt.% to 11 wt.% and the ettringite content ranges from 0 wt.% to 27 wt.%.
- Average total sulphur content of the representative CPT materials ranges from 3.4 wt.% to 9.2 wt.% and is dominated by sulphate. The CPT contains a higher total sulphur content compared to CPB because the CPT material contains process wastes that are almost entirely composed of calcium sulphate minerals. The high binder CPT materials contain a high neutralization potential and are classified as NPAG. The low binder CPT materials contain a neutralization potential at least an order of magnitude lower than the representative high binder materials and have an uncertain or PAG classification.

- The representative CPT materials contain enriched solid-phase concentrations of arsenic, bismuth, copper, lead, molybdenum, selenium, sulphur, and uranium. Constituents with a high leachability potential for representative CPT materials identified from the short-term leach testing include aluminum, arsenic, chromium, lead, molybdenum, selenium, silver, strontium, sulphate, and thallium.
- Similar to CPB, the lower binder variant of the CPT materials contained the highest average radioactivity (i.e., gross alpha activity 3,075 Bq/g and gross beta activity 1,075 Bq/g) compared to the higher binder variant (i.e., gross alpha activity 1,725 Bq/g and gross beta activity 548 Bq/g). Radioactivity and radiochemical speciation analysis indicate that some radioactivity is mobilized during short-term leach testing with gross alpha activity of 40 Bq/L to 60 Bq/L and gross beta activity of 13 Bq/L to 36 Bq/L in the SFE leachate. Radionuclide species with the highest leachable concentrations in CPT leachates were radium-226 (i.e., 6.9 Bq/L to 17 Bq/L) and radium-228 (i.e., 2.1 Bq/L to 3.4 Bq/L).
- Elemental liberation rates from CPT materials under advective mass transfer conditions indicate that the initial porewater quality is circumneutral to alkaline (i.e., pH 7.4 to 11) and remains slightly alkaline (i.e., pH 7.5 to 9) after 30 pore volume replacements (Figure 2-5). The metal liberation rates follow ordered rate kinetics (i.e., flushing) with the highest concentrations recorded in the first two pore volume replacements and decrease, in most cases, by several orders of magnitude at five pore volume replacements (Figure 2-6, for example).
- Diffusive mass flux values for representative CPT materials are greatest during the initial leaching period. Mass flux values are influenced more by the percentage of binder in the sample than the composition of the material. Lower binder (i.e., or lower strength) materials generally exhibit greater diffusive mass flux values (Figure 2-7), with a few exceptions (e.g., barium and lead).

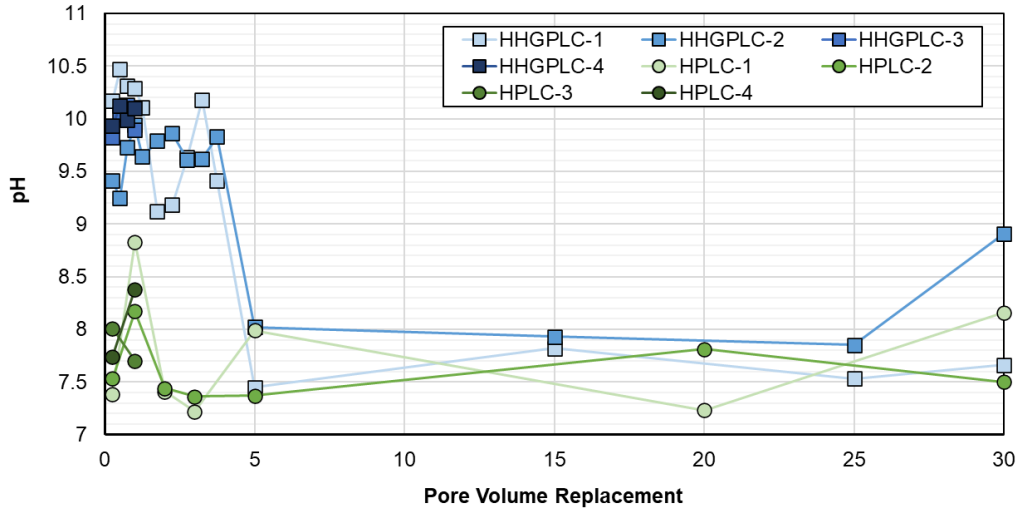
Table 2-6: Selected Average Geotechnical, Geochemical, and Radiological Properties of Representative Cemented Paste Tailings Materials

Characteristic	Parameter	Units	HPLC ^(a)	HPHC ^(a)	HHGPLC ^(a)	HHGPHC ^(a)
Geotechnical	Hydraulic conductivity	m/s	1.0×10^{-08}	7.2×10^{-10}	3.2×10^{-08}	2.8×10^{-09}
	Porosity	ratio	0.60	0.61	0.71	0.69
Geochemical (SFE)	pH	pH units	8.8	12	10	12
	Sulphate	mg/L	1,690	1,610	2,180	1,950
	Uranium	mg/L	0.069	0.020	0.014	0.012
Geochemical (MTP first pore volume)	pH	pH units	8.0	n/a	10	n/a
	Aluminum	mg/L	0.99	n/a	1.0	n/a
	Uranium	mg/L	0.40	n/a	0.038	n/a
Geochemical (LEAF mass flux – first three leach events)	Sulphate	mg/m ² /s	0.81	0.0027	1.6	0.45
	Uranium	mg/m ² /s	0.000084	0.000072	0.00026	0.000032
Radiological (SFE)	Lead-210	Bq/L	0.40	8.0	0.40	4.0
	Radium-226	Bq/L	17	7.2	11	6.9

a) Composite sample definitions are provided in Table 2-2.

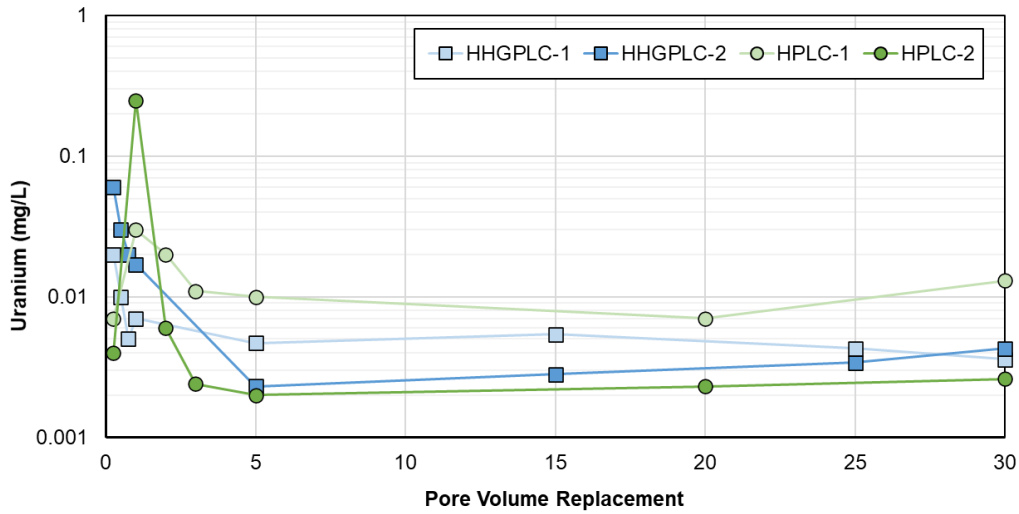
n/a = not applicable; MTP = modified triaxial permeability; LEAF = Leaching Environmental Assessment Framework; Bq/L = becquerels per litre; SFE = shake flask extraction.

Figure 2-5: pH versus Pore Volume Replacement for Low Binder Cemented Paste Tailings Material



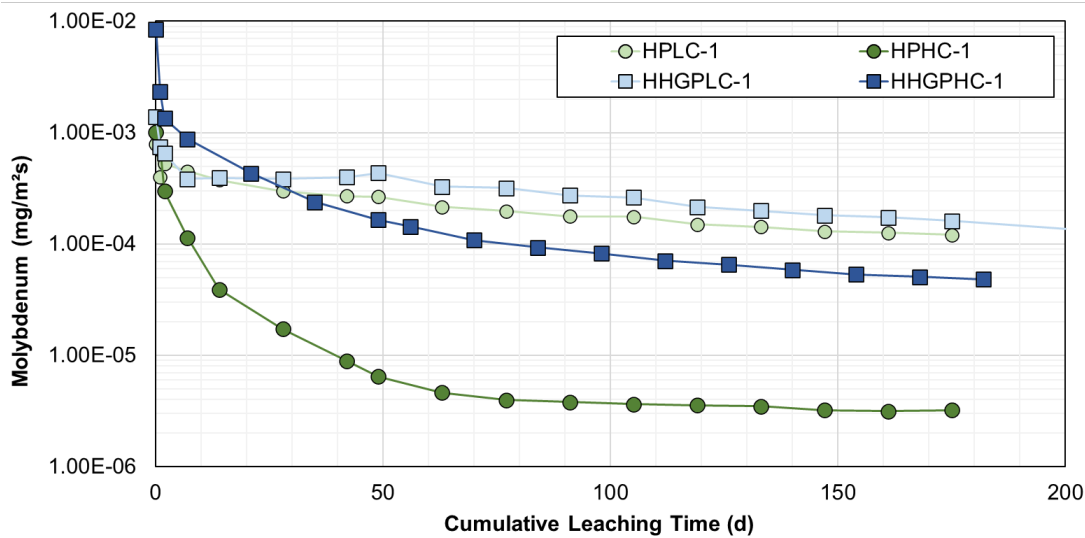
Note: Composite sample definitions are provided in Table 2-2.

Figure 2-6: Uranium Concentration versus Pore Volume Replacement for Low Binder Cemented Paste Tailings Material



Note: Composite sample definitions are provided in Table 2-2. Uranium was chosen as an example to illustrate the metal liberation trends that were observed in the CPT.

Figure 2-7: Mass Flux versus Cumulative Leaching Time for Representative Cemented Paste Tailings Materials



Note: Composite sample definitions are provided in Table 2-2.

3 SOURCE TERM DERIVATION

3.1 Conceptual Model for the Underground Disposal Areas

Data analysis and interpretation from studies completed in support of the EIS and feasibility assessment for the Project were used to develop conceptual models representative of processes that will affect solute mass loading rates from backfilled CPB and CPT in the mine stopes and UGTMF.

The release of solutes from CPB and CPT during Operations is expected to be limited since the paste composition is designed to not release water after deposition (NexGen 2021a). Additionally, groundwater reporting to the underground mine would be pumped to the surface and treated during Operations. As such, the underground mine will be under hydraulic containment and release of mining-affected groundwater from potential underground sources to the surrounding environment will not occur (EIS Section 8).

Upon completion of mining and backfilling, the underground will be re-flooded and groundwater pressures will return to natural hydrostatic conditions (EIS Section 8). The backfilled CPB and CPT will be inundated, and two mass transfer mechanisms will be established that will determine the mass loading rates from these materials to the surrounding groundwater:

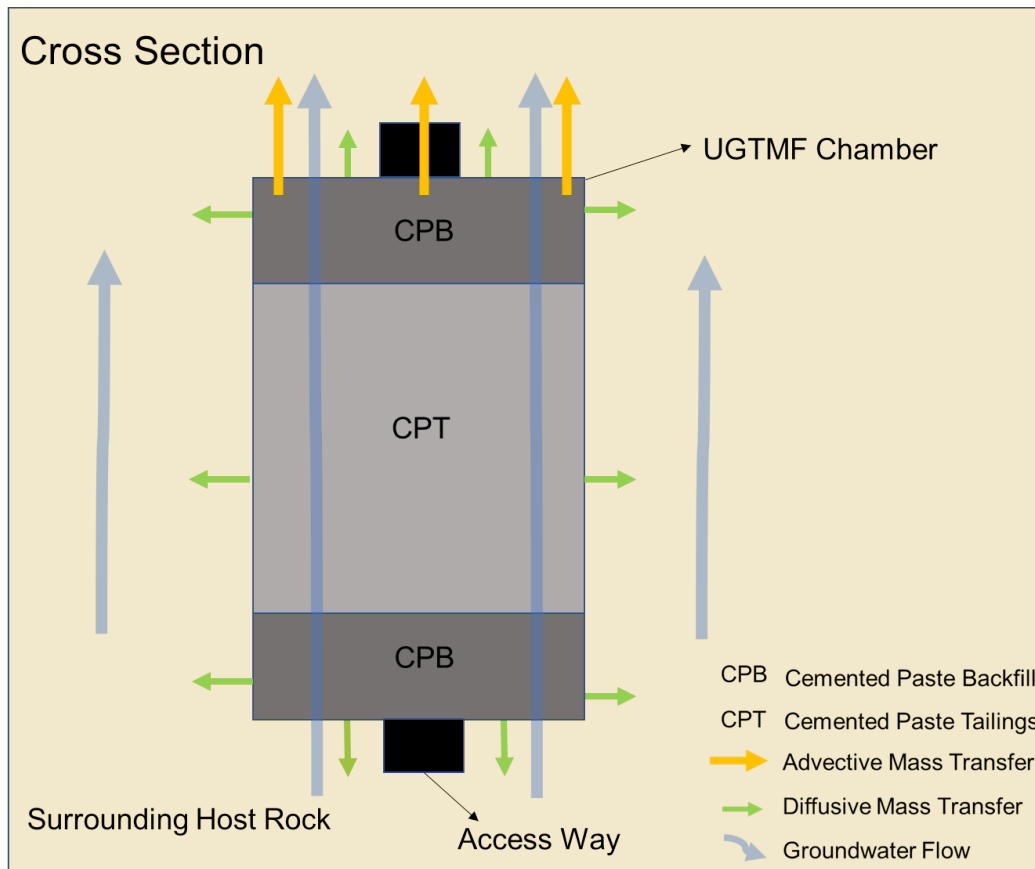
- leaching of solutes from CPB and CPT as groundwater moves through the material under regional groundwater flow gradients (i.e., advective mass transfer); and
- leaching of solutes from CPB and CPT due to concentration differences between the material surface, the material porewater, and the surrounding groundwater (i.e., diffusive mass transfer).

The amount and rate at which constituents are released from CPB and CPT under advective and diffusive mass transfer mechanisms are governed by the physical properties of the CPB/CPT, surrounding host rock, and the interaction with percolating groundwater.

Conceptual models for advective and diffusive mass transfer aim to describe the main physical and chemical/radiological processes associated with the backfilled mine stopes and UGTMF. These conceptual models form the basis for the mine stopes and UGTMF source term derivation. Conceptual figures illustrating the general direction of advective and diffusive mass transfer in a UGTMF chamber are provided in Figure 3-1 and Figure 3-2.

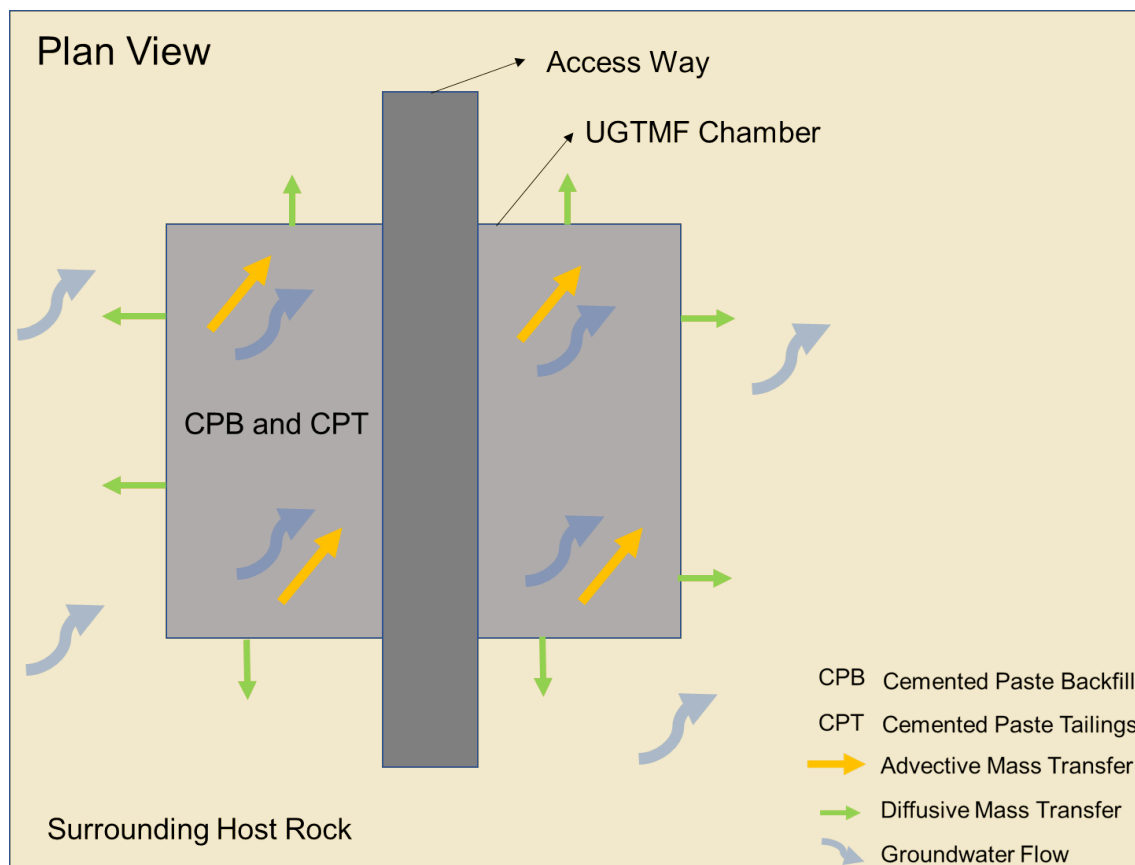
Daughter products formed by the radioactive decay of uranium-238, including thorium-230, radium-226, lead-210, and polonium-210, are present in the CPB and CPT. These radionuclides are subject to both advective and diffusive mass transfer mechanisms, and ongoing radioactive decay (i.e., ingrowth) is expected to occur during transport through the CPB and CPT. Half-life periods for these decay series range from tens of thousands of years in the case of uranium-238 and thorium-230 to relative short periods such as 138 days in the case of polonium-210.

Figure 3-1: Schematic Representation of a Cross Section View of an Underground Tailings Management Facility Chamber



Note: post-closure groundwater flow would be vertical (Section 8)

Figure 3-2: Schematic Representation of a Plan View of an Underground Tailings Management Facility Chamber



Note: post-closure groundwater flow direction is expected to be vertical (EIS Section 8)

3.1.1 Advective Mass Transfer

The CPB and CPT will be in direct hydraulic connection with the surrounding groundwater when the mine re-floods and mass transfer from these materials will be subject to regional groundwater flow gradients. Initially, groundwater will flow into the CPB and CPT and mix with existing dissolved constituents in the pore space. Once the CPB and CPT materials are saturated, porewater will flow from the backfilled materials in the downgradient direction from the mine stopes and UGTMF at rates determined by the surrounding paleoweathered basement, basement bedrock, fault zones and shear zones.

After the pore space in the CPB and CPT is replaced with percolating groundwater, the water will continue to interact with the material matrix. Chemical reactions will take place that transform primary minerals into dissolved solutes and secondary minerals. These chemical reactions are expected to attenuate following ordered rate kinetics, resulting in a decrease in mass transfer over time.

Minerals are the ultimate source of solutes in the CPB and CPT, and their solubility determines the rate of mass release. Both CPB and CPT consist of neutralized leach residue, which consists mostly of quartz and aluminosilicate minerals (i.e., chamosite, clinocllore, and muscovite). These aluminosilicate minerals represent the most chemically resistant minerals that remain after acid leaching in the uranium extraction process and

have low solubilities. The CPT will also contain process wastes that consist of calcium sulphate minerals (i.e., anhydrite and gypsum), which are more soluble than the aluminosilicate minerals. The CPB and CPT will contain different binder types. Higher proportions of binder are associated with the formation of cementitious minerals such as alite, belite, tricalcium aluminate, and ettringite.

In addition to the initial mineralogical composition of the material, the magnitude and rate of mass release from CPB and CPT will also be determined by the following:

- the quality of the pre-existing porewater;
- the mass of soluble components associated with the pore space, particularly residual OPC binder and soluble fractions of the process wastes; and
- the rate at which groundwater flows into the backfilled mine stopes and UGTMF; this rate is determined by the hydraulic conductivity of CPB and CPT and the groundwater flow gradient.

3.1.1.1 **Key Chemical Reactions**

Key chemical reactions that will take place as groundwater percolates through the CPB and CPT include the following:

- **Dissolution and precipitation reactions:** Dissolution of primary minerals is expected to result in soluble chemical species as free ions or complexes with a ligand. The precipitation of secondary minerals will depend on concentration of ions in solution, pH, and mineral saturation indices.
- **Oxidation and reduction reactions:** A redox differential is expected between the percolating groundwater and the CPB and CPT porewater where the groundwater will have a more reduced redox potential. Changes in redox can lead to mineral precipitation, elemental sorption, mineral dissolution, and elemental desorption.
- **Hydrolysis:** Hydrolysis reactions are important weathering processes for silicate minerals that take place over geological time frames due to the slow kinetics of these reactions.
- **Hydration reactions:** Hydration reactions combine substances with water and are expected to be associated with gypsum precipitates and OPC binder in the composite materials.
- **Ion exchange and adsorption:** Ion exchange is a mechanism through which dissolved chemical species may be removed from solution. Ion exchange can occur with constituents in solution that exchange with weakly held ions, or ions adsorbed to positively or negatively charged surfaces. Iron and aluminum oxyhydroxide minerals have high unit mass ion exchange capacities. Surface charges on kaolinite and oxyhydroxides can vary from negative to positive depending on pH. At alkaline pH (e.g., as in column test leachate), the minerals have more negative surface charges that increase their capacity to sorb metal cations.
- **Radioactive decay and ingrowth:** Radionuclides may decay, or be created by ingrowth, as groundwater percolates through the CPB and CPT. Ingrowth can produce a daughter element whose geochemical characteristics differ markedly from the mother element. These changes in geochemical characteristics will affect the mobility of the daughter element.

3.1.2 Diffusive Mass Transfer

Diffusion will occur when the mine re-floods and the CPB and CPT are in direct hydraulic connection with the surrounding groundwater. Concentration gradients will be established between the surrounding groundwater and CPB and CPT. These concentration gradients will result in diffusive mass transfer between the CPB, CPT and the surrounding groundwater.

The magnitude and rate of diffusive mass transfer from the backfilled CPB and CPT will be determined by:

- **Concentration differential:** Diffusion rates will be determined by the magnitude of the concentration differential between the CPB, CPT and the surrounding groundwater. Concentrations associated with the CPB and CPT are defined by the porewater quality of the materials, the soluble constituents on the surface of the wastes, and the primary minerals exposed on the surface of the wastes.
- **Diffusion coefficient:** Each constituent is associated with a unique diffusion coefficient that affects the diffusion rate.
- **Hydraulic contact area:** Groundwater flow in the surrounding crystalline basement rock is associated with fractures. Where these fractures connect with the underground mine stopes and UGTMF, a hydraulic connection between the surrounding groundwater and the CPB and CPT is created. The density of the fracture network determines the surface area exposure of the CPB and CPT to the groundwater, which determines the quantum of mass transfer taking place.

3.2 Source Term Derivation Approach

The main objective of the mine stopes and UGTMF source terms is to predict the mass loading rate or leachate quality determined by advective and diffusive mass transfer processes at post-closure. To achieve this objective, a modelling approach was used that is supported by a geochemical characterization program with empirical laboratory measurements of key mass transfer processes. The approach followed in the geochemical source term derivation is consistent with guidelines provided by Mine Environment Neutral Drainage (MEND 2009) and International Network for Acid Prevention (INAP 2009).

Three source term models were developed to represent each of the underground disposal areas that will host CPB and CPT, including primary stopes, secondary stopes, and UGTMF. Each source term model also includes separate components for advective and diffusive mass transfer, and accounts for different material types and strength requirements for each disposal area. The geochemical characterization program included the development and compositing of representative CPB and CPT samples, and characterization methods (i.e., kinetic testing methods) that were designed to support this source term derivation approach.

Given the complexity of the physical and chemical processes that determine the magnitude and rate of advective and diffusive mass transfer from the underground mine stopes and UGTMF (Section 3.1, Conceptual Model for the Underground Disposal Areas), simplifying assumptions and bounding arguments were used in the source term models to reduce the number of parameters/variables to those that can be measured using laboratory tests.

The general assumptions that form the basis of the source term models and their underlying advective and diffusive mass transfer mechanisms are summarized below:

- Groundwater flow through the CPB and CPT is assumed to be saturated matrix flow, based on the expected homogenous nature of the materials. This type of flow maximizes the interaction between minerals in the waste and the percolating groundwater, and the consequent leaching of solutes. Should cracks form in the CPB and CPT before flooding of the mine, it will reduce the interaction between the percolating groundwater and the minerals in the wastes, and result in a lower mass flux compared to the matrix flow assumption.
- Source terms were developed to represent a range of binder conditions (low to high cement/slag) and process wastes to account for potential variability in operating conditions. The low and high cement/slag binder materials, plus the ratio of process wastes for CPT materials, form an envelope of potential operating conditions. It is assumed that variability in actual operating conditions will result in CPB and CPT compositions that fall within this envelope of binder and process wastes.
- Concentrations of nitrogen species were based on data from composite materials developed in pilot scale testing. Nitrogen species loading from residual blasting products on the ore chemistry and process plant circuit chemistry is unknown and not considered as part of the source term derivation. This assumption is therefore not conservative, and care should be taken in interpreting nitrogen species loading from the tailings. The effect of nitrogen loading from residual blasting products on the mine water system was further assessed and quantified in TSD XVIII, Site-Wide Water Balance and Water Quality Modelling Report.
- In developing input data for source term calculations, reported concentrations for certain constituents were below the analytical detection limit. In such instances the actual value was assumed to be equal to one-half the detection limit (TSD XVI).
- Advective mass transfer rates are approximated by laboratory-measured porewater qualities as a function of pore volume replacements over time. Samples of equivalent pore volumes were taken at multiple pore volume replacement intervals during modified triaxial permeability (MTP) tests of representative CPB and CPT materials.
- Diffusive mass transfer from the CPB and CPT is approximated by laboratory-measured mass transfer rates (i.e., release rates) of inorganic solutes under diffusion-controlled release conditions. The Leaching Environmental Assessment Framework (LEAF) test method provides intrinsic material parameters for release of inorganic solutes under mass transfer controlled leaching conditions and was conducted using representative samples of CPB and CPT.

3.3 Methods

The numerical modelling approach for each of the source terms is summarized in Table 3-1. As noted in Section 3.2, Source term Derivation Approach, a base case and upper case were modelled for each component based on the replicate variability of the materials. The numerical derivation of each mass transfer component is summarized in the following subsections.

Table 3-1: Numerical Model Approach for the Primary Stopes, Secondary Stopes, and Underground Tailings Management Facility

Source		Advective Mass Transport	Diffusive Mass Transport
Primary stopes	Stope	<ul style="list-style-type: none"> Derivation of initial porewater quality using MTP and SFE test results of CPB representative materials Binder content considered in selection of representative materials 	<ul style="list-style-type: none"> Calculation of initial observed diffusivity using LEAF test results of CPB representative materials Binder content considered in selection of representative materials
	Sill pillar		
Secondary stopes	Stope		
	Sill pillar		
UGTMF	Cap and plug	<ul style="list-style-type: none"> Derivation of initial porewater quality using MTP and SFE test results of CPT representative materials Binder and process waste content considered in selection of representative materials 	<ul style="list-style-type: none"> Calculation of initial observed diffusivity using LEAF test results of CPT representative materials Binder and process waste content considered in selection of representative materials
	Chambers		

UGTMF = underground tailings management facility; MTP = modified triaxial permeability; CPB = cemented paste backfill; CPT = cemented paste tailings; LEAF = Leaching Environmental Assessment Framework; SFE = shake flask extraction.

3.3.1 Numerical Derivation of Advection Mass Transfer Components

The rate and volume of groundwater flow through CPB and CPT in the underground mine stopes and UGTMF were predicted in the groundwater solute transport model (EIS Section 8). As such, concentrations (i.e., mass per unit volume) defining the quality of water exiting the CPB and CPT were provided as inputs to the solute transport model, and were combined with predicted flow rates (i.e., volume per unit time) to calculate mass loads.

The MTP test results for representative CPB and CPT materials provide an approximation of the porewater qualities that will move downgradient as groundwater percolates through the materials. This MTP data forms the basis for the calculation of source qualities for the underground mine stopes and UGTMF. At the time of this source term derivation, MTP testing was only conducted on low binder versions of the CPT and CPB materials (HLC-S, HPLC, and HHGPLC), and analyses were limited to pH and trace metals due to the small volumes of water recovered from the materials.

The following approach was used to calculate porewater concentrations for the underground mine stopes and UGTMF source terms:

- Porewater qualities for low and high binder versions of CPB and CPT were calculated using a combination of MTP and SFE test results.
- Base case and upper case porewater qualities were differentiated for CPB and CPT.
- Source terms calculations reflected the material types and uses proposed for underground mine stopes and UGTMF (see Table 2-1).

3.3.1.1 Calculation of Porewater Qualities for Low Binder and High Binder Cemented Paste Backfill and Cemented Paste Tailings

Average trace metal MTP concentrations were used to calculate porewater qualities for low binder versions of CPB and CPT. Low binder materials have a higher hydraulic conductivity compared to the high binder samples, resulting in more conservative (i.e., higher) advective mass transfer rates. Data used in the calculations consisted of data collected up to and including one pore volume replacement.

Since major ion and radionuclide concentrations could not be measured in the MTP tests because of low sample volumes, these concentrations were calculated by adjusting the short-term leach test (i.e., SFE) results to represent the solid:liquid ratios by volume in the MTP test conditions. The SFE mass loads for representative low binder CPB and CPT materials were adjusted using the MTP sample mass and sample pore volume according to the following equations:

$$SFE \text{ Mass Load } \left(\frac{mg}{kg} \right) = \frac{SFE \text{ concentration } \left(\frac{mg}{L} \right) \times SFE \text{ leachate volume } (L)}{SFE \text{ mass of material } (kg)}$$

$$Concentration \left(\frac{mg}{L} \right) = \frac{SFE \text{ mass load } \left(\frac{mg}{kg} \right) \times MTP \text{ mass of material } (kg)}{MTP \text{ sample pore volume } (L)}$$

Major ion, trace metal, and radionuclide concentrations for high binder versions of the CPB and CPT were then calculated assuming the concentration ratio of high binder to low binder is equal to the ratios observed in the SFE test results.

3.3.1.2 Base Case and Upper Case Source term Calculations

After the predicted qualities for low and high binder versions of CPB and CPT were developed, the representative materials for CPB and CPT were proportioned to develop a base case and upper case quality for each material type. The predicted concentrations were proportioned according to the specifics outlined in Table 3-2. For the upper case scenarios, the highest pH was chosen.

Table 3-2: Methods for Cemented Paste Backfill and Cemented Paste Tailings Porewater Quality Calculations

Material	Case	Method ^(a)
CPB	Base	HHC-S and HLC-S solutions were mixed in a 1:5.7 ratio, based on the binder strength needed in the primary stopes. pH was calculated by mixing HHC-S and HLC-S SFE solutions in a 1:5.7 ratio in PHREEQC.
CPB	Upper	Maximum concentration between HHC-S and HLC-S was chosen for each constituent. pH was the maximum pH recorded for HHC-S and HLC-S SFE solutions.
CPT	Base	Maximum concentration between HHGPLC and HPLC was chosen for each constituent. Low binder materials were chosen for base case based on binder strength required in the UGTMF. Maximum concentration was chosen because ratio between HHGPLC and HPLC is unknown at this time. pH was median of HHGPLC MTP values.
CPT	Upper	Maximum concentration among HHGPLC, HPLC, HHGPHC, and HPHC was chosen for each constituent. pH was the maximum pH recorded for HHGPLC, HPLC, HHGPHC, and HPHC SFE solutions.

a) Composite sample definitions are provided in Table 2-2.

CPB = cemented paste backfill; CPT = cemented paste tailings; UGTMF = underground tailings management facility; SFE = shake flask extraction; MTP = modified triaxial permeability.

3.3.1.3 *Stope and Underground Tailings Management Facility Material Compositions*

Source terms were calculated for the underground mine stopes and UGTMF considering the material types and ratios that will be deposited in each area. The methods followed in the source term calculations are summarized in Table 3-3. As noted in Section 2.1, Tailings and Process Waste Disposal, the UGTMF was assumed to consist of 85% CPT-filled chambers and 15% CPB-filled plugs and caps. It was also assumed that upset conditions may occur for a total of 10% of Operations where a UGTMF chamber is not available, and CPT is therefore disposed in the secondary stopes.

Table 3-3: Methods for Advective Mass Transfer Source term Components

Facility Source term	Method
Primary stope base case	Equal to CPB base case
Primary stope upper case	Equal to CPB upper case
Secondary stope base case	Mixed solution composed of 90% CPB base case and 10% CPT base case
Secondary stope upper case	Mixed solution composed of 90% CPB upper case and 10% CPT upper case
UGTMF base case	Mixed solution composed of 15% CPB base case and 85% CPT base case
UGTMF upper case	Mixed solution composed of 15% CPB upper case and 85% CPT upper case

UGTMF = underground tailings management facility; CPB = cemented paste backfill; CPT = cemented paste tailings.

3.3.2 Numerical Derivation of Diffusion Mass Transfer Components

Based on the LEAF test method (USEPA 2017), an observed diffusivity was calculated in units of square metres per second (m^2/s) to represent the diffusion coefficient for each constituent. The diffusion coefficient was used directly in the solute transport model (Section 8) to develop a mass loading from diffusive mass transfer for each constituent of concern. According to the LEAF test method, observed diffusivity was calculated according to the following equation:

$$\text{Observed diffusivity for interval } i = \pi \left[\frac{C_i \times V_i}{A \times 2 \times \rho \times C_0 \times (\sqrt{t_i} - \sqrt{t_{i-1}})} \right]^2$$

where:

C_i is the constituent concentration in the eluate for leaching interval i (mg/L);

V_i is the eluate volume in interval i (L);

A is the external geometric surface area exposed to the eluent (m^2);

ρ is the sample density (kg/m^3 dw);

C_0 is the initial leachable content (mg/kg);

t_i is the cumulative time at the end of the current leaching interval (s); and

t_{i-1} is the cumulative time at the end of the previous leaching interval (s).

The observed diffusivity (i.e., diffusivity coefficient) was calculated for each leach event of the representative CPB and CPT materials. Since observed diffusivity is dependent on the initial leachable concentration of the material and varies slightly over the course of the testing period, the median value of all leach periods was calculated for low and high binder CPB and CPT materials.

Similar to the advective mass transfer component, source terms were calculated by considering the material types that will be deposited in each area. Median and maximum CPB values were used to develop the mine stope base case and upper case source terms, respectively. Median and maximum CPT values were used to develop the UGTMF base case and upper case source terms, respectively (Table 3-4).

Table 3-4: Methods for Diffusive Mass Transfer Source term Components

Facility Source term	Method ^(a)
Primary stope base case	Median value between HLC-S and HHC-S materials
Primary stope upper case	Maximum value between HLC-S and HHC-S materials
Secondary stope base case	Equal to primary stope base case
Secondary stope upper case	Equal to primary stope upper case
UGTMF base case	Median value among HPLC, HPHC, HGPLC and HGPHC materials
UGTMF upper case	Maximum value among HPLC, HPHC, HGPLC and HGPHC materials

a) Composite sample definitions are provided in Table 2-2.

3.4 Conservatism

Bounding arguments were made to the derivation approach to establish a conservative case for the mine stopes and UGTMF source terms to intentionally overestimate the mass loading from these disposal areas. The bounding arguments were chosen to specifically address the uncertainties associated with input parameters, such as the kinetics of mineral weathering and flow of water within the wastes, as well as the lack of analogue sites and data where this tailings disposal strategy was implemented. The bounding arguments and their associated conservatism are summarized below:

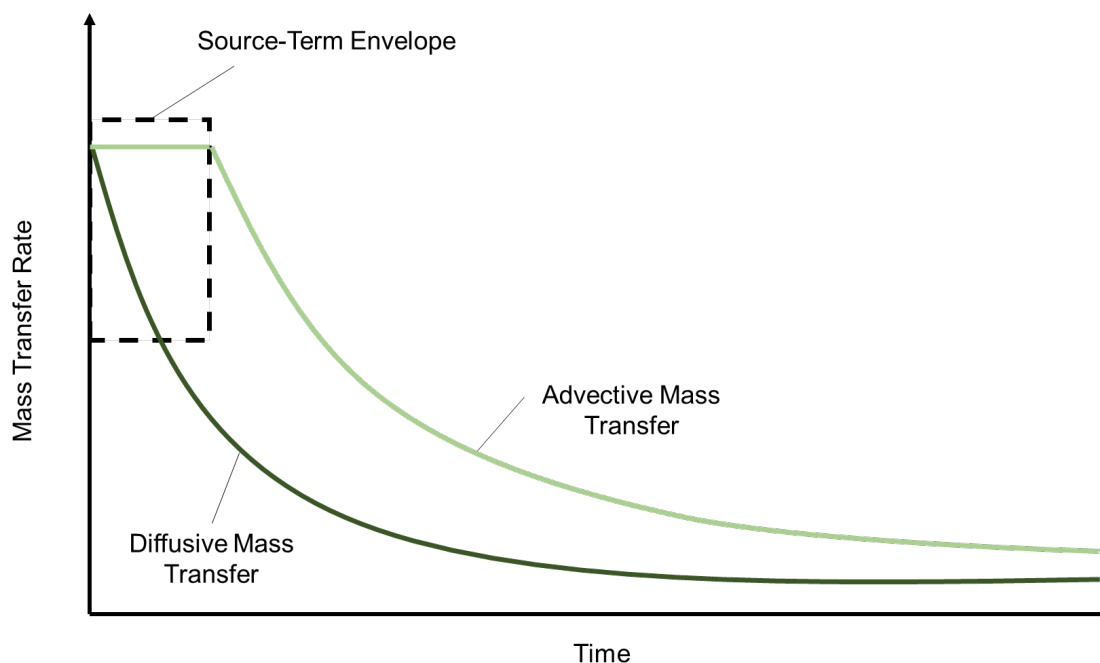
- CPB and CPT materials were constituted using the neutralized leached residue from tailings produced from high-grade triuranium octoxide (U_3O_8) variants of the Rook I ore grade distribution (NexGen 2021a), and therefore represent a conservative material composition for uranium and associated daughter elements.
- Laboratory-measured mass transfer rates and concentrations are conservative.
 - Concentrations measured in the MTP tests for representative CPB and CPT materials represent conservative mass transfer rates compared to site conditions because deionized water was used as an eluent in the test. The deionized water contains a lower total dissolved solids and ionic strength compared to the groundwater, which will result in higher dissolution rates and greater mass release rates.
 - Diffusive mass transfer is a function of the concentration differential between the surface of the CPB, CPT, and the surrounding groundwater. Since the LEAF tests were conducted with deionized water (i.e., low ionic strength), a greater concentration gradient was created which results in the measurement of conservative mass transfer rates.
- Advective and diffusive mass release is assumed to be constant over time and initial mass transfer rates were used.
 - The composition of CPB and CPT represent a finite mass of potential leachable solutes and radionuclides when they are deposited underground. After flooding, the initial mass transfer rates

from the materials are expected to be the highest and then decline over time as solutes are released through mass transfer processes following typical ordered rate kinetics (i.e., decaying source terms).

- Results from kinetic laboratory tests (i.e., MTP and LEAF) support this assumption and indicate that the greatest mass transfer rates occur within the initial measurements and decrease over time. The LEAF test mass transfer rates decrease over time following ordered rate kinetics, whereas results from MTP tests indicate a significant (i.e., order of magnitude) decrease in mass transfer rates after the first two pore volume replacements (TSD XVI). Figure 3-3 provides a schematic representation of these observations.
- Assuming that mass transfer rates will be constant over time and at rates equivalent to the highest transfer rates, (e.g., see source term envelope in Figure 3-3) the source term predictions are conservative and represent an overestimation of future solute mass loading.
- Secondary mineral and ion exchange controls on advective mass transfer rates were ignored.
 - The formation of secondary minerals in the CPB and CPT can reduce mass transfer rates and porewater concentrations for elements associated with these minerals. Secondary minerals can co-precipitate and provide ion exchange sites that absorb metals and radionuclides from solution. The potential for secondary minerals to form as groundwater percolates through the CPB, and CPT was assessed using geochemical speciation modelling (Section 3.4.1, Evaluation of Secondary Mineral Controls).
 - Geochemical speciation modelling indicates the potential for several secondary minerals to form and control the concentration of metals and radionuclides in solution. Ignoring the effect of secondary mineral controls on the advective mass transfer rates is therefore conservative and represents an overestimation of future solute mass loading.
- A range of composite materials were tested in the characterization program that represent the variability in composition of CPB and CPT materials. For each composite material tested, four replicate samples were also analyzed to represent the variability in each of the representative materials. To express this variability, a best estimate, or base case, and a reasonable upper bound estimate, or upper case, were developed. The base case estimates were developed using average or median statistics and the upper case estimates were developed using maximum statistics.

Applying the above bounding arguments (which applies to both the base case and upper case) results in overestimation of the source terms and their respective mass transfer rates. These bounding arguments are reasonably conservative and aim to account for the many uncertainties and limitations associated with predicting site-specific, future behaviour of the CPB and CPT in the stopes and UGTMF. The sensitivity of these bounding arguments and the associated conservatism is assessed in the groundwater solute transport model (EIS Section 8).

Figure 3-3: Approach to Conservatism in Source Term Development



3.4.1 Evaluation of Secondary Mineral Controls

The potential for secondary minerals to form as groundwater percolates through the CPB and CPT was assessed using geochemical speciation modelling. Secondary minerals can co-precipitate and provide ion exchange sites that absorb metals and radionuclides from solution. The main objective of this assessment was to confirm the conservatism of the bounding argument (Section 3.4, Conservatism) that ignoring these controls will result in conservative source term predictions.

The predicted porewater qualities (i.e., base and upper cases) for the CPB and CPT were equilibrated using the geochemical speciation and equilibration model PHREEQC version 3.3.5 (Parkhurst and Appelo 1999). Due to the high ionic strength and alkalinity of the estimated porewater qualities, the ThermoChimie database (SIT.DAT) was chosen for the simulation. The ThermoChimie database provides an accurate and consistent set of data specifically chosen for use in modelling the behaviour of radionuclides in mine wastes, engineered barriers, and both near surface and deeper repositories (Duro et al. 2012). In instances where the ThermoChimie database lacked thermodynamic data for expected mineral phases, other databases such as the Lawrence Livermore National Laboratory (LLNL.DAT), MINTEQ.V4.DAT, WATEQ4F.DAT, and CEMDATA.DAT were used to supplement the thermodynamic data. The thermodynamic data added to the ThermoChimie database from other databases are shown in Table 3-5.

Table 3-5: Thermodynamic Data Added to the ThermoChimie Database

Database	Thermodynamic Data
LLNL.DAT	Element master species, species and mineral phases were added for beryllium, nitrite, titanium, vanadium, and thallium
MINTEQ.V4.DAT	Nickel molybdate (NiMoO_4) and ferric arsenate (FeAsO_4)
WATEQ4F.DAT	Surface complexation species
CEMDATA.DAT	Thaumasite and Kuzel's salt

The geochemical modelling was conducted by bringing the aqueous solutions to thermodynamic equilibrium and assessing chemical speciation and mineral solubility as follows:

- Non-electrically neutral input solutions were adjusted to neutrality through the addition of chloride, when anion deficient, or sodium, when cation deficient. Both are ions that are generally highly mobile and form highly soluble salts and, therefore, are unlikely to be associated with reactions involving the fate and transport of the key metals, metalloids, and complexes.
- Input oxygen partial pressure was controlled by fixing the oxidation-reduction potential (redox). To evaluate the sensitivity of mineral solubility to redox, a range of oxidation-reduction potential values were assigned, including -250 millivolts (mV), 0 mV, +250 mV, or +500 mV. This range of oxidation-reduction potential values were assumed to represent the oxidized nature of the CPB and CPT and anticipated reducing groundwater conditions at depth.
- The pH values of the solutions were calculated as an outcome of the equilibration.
- Temperature sensitivity was not evaluated, and solutions were assumed to be at 25°C to be consistent with thermodynamic data for minerals in the thermodynamic databases.

Key results of the geochemical speciation modelling are summarized below:

- Potential secondary mineral phases that can control the concentration of uranium in the porewater solutions of CPB and CPT includes calcium diuranate ($\text{CaU}_2\text{O}_7 \cdot 3\text{H}_2\text{O}$), uraninite (UO_2), and becquerelite ($\text{Ca}[\text{UO}_2]_6\text{O}_4[\text{OH}]_6 \cdot 8\text{H}_2\text{O}$). The potential for these secondary mineral phases to control uranium concentrations is a function of the solution redox, pH, and type of material. The precipitation of these secondary mineral phases will reduce the concentration of uranium in the simulated porewater solutions.
- Potential secondary mineral controls were also identified for aluminum, barium, calcium, iron, lead, manganese, molybdenum, nickel, nitrogen species, sulphur, and uranium. These secondary mineral phases include Friedel's salt ($\text{Ca}_2\text{Al}[\text{OH}]_6[\text{Cl},\text{OH}] \cdot 2\text{H}_2\text{O}$), lead molybdate (PbMoO_4), manganese dioxide (MnO_2), manganite ($\text{MnO}[\text{OH}]$), monosulphoaluminate ($\text{Ca}_4\text{Al}_2[\text{SO}_4][\text{OH}]_{12} \cdot 6\text{H}_2\text{O}$), calcium arsenate ($\text{Ca}[\text{ASO}_4]$) and nickel hydroxide ($\text{Ni}[\text{OH}]_2$). As with uranium, the potential for these secondary mineral phases to control the concentrations of the respective metals in solution is a function of the solution redox, pH, and type of material. In all cases, the precipitation of these secondary minerals will result in a reduction in the concentration of the respective metals.

The geochemical speciation modelling of estimated porewater qualities for the advective mass transfer components of the mine stopes and UGTMF source terms indicate the potential for secondary mineral phases to precipitate from solution and reduce the concentration of the elements (i.e., constituting the mineral phases) in the porewater solutions. Ignoring these controls in the source term derivation process is therefore a conservative bounding argument.

4 RESULTS

4.1 Primary Stopes Source Terms

Derived source terms for the primary stopes are provided in Table 4-1 and consist of estimated porewater quality in units of mg/L (unless indicated otherwise) and calculated diffusivity in units of m²/s.

Table 4-1: Primary Stopes Source Terms

Constituent	Units	Advection (Porewater Quality)		Units	Diffusivity	
		Base Case	Upper Case		Base Case	Upper Case
pH	pH units	11	12	n/a	n/a	n/a
Alkalinity, as CaCO ₃	mg/L	970	4,176	m ² /s	1.7 × 10 ⁻¹⁰	1.8 × 10 ⁻¹⁰
Ammonia, as N	mg/L	3.3	3.5	m ² /s	3.5 × 10 ⁻¹⁰	3.5 × 10 ⁻¹⁰
Chloride	mg/L	716	754	m ² /s	8.2 × 10 ⁻¹¹	1.6 × 10 ⁻¹⁰
Fluoride	mg/L	5.8	6.5	m ² /s	1.9 × 10 ⁻¹⁰	2.5 × 10 ⁻¹⁰
Nitrite, as N ^(a)	mg/L	0.025	0.026	m ² /s	9.2 × 10 ⁻⁰⁹	9.2 × 10 ⁻⁰⁹
Nitrate, as N ^(a)	mg/L	0.020	0.020	m ² /s	1.5 × 10 ⁻⁰⁷	2.8 × 10 ⁻⁰⁷
Phosphate, as P	mg/L	0.027	0.028	m ² /s	3.6 × 10 ⁻⁰⁸	3.6 × 10 ⁻⁰⁸
Aluminum	mg/L	3.6	27	m ² /s	1.0 × 10 ⁻⁰⁹	1.5 × 10 ⁻⁰⁹
Antimony	mg/L	0.0085	0.01	m ² /s	1.5 × 10 ⁻⁰⁹	2.9 × 10 ⁻⁰⁹
Arsenic	mg/L	0.49	0.74	m ² /s	1.8 × 10 ⁻¹⁰	3.4 × 10 ⁻¹⁰
Barium	mg/L	0.030	0.059	m ² /s	7.8 × 10 ⁻¹⁰	1.5 × 10 ⁻⁰⁹
Beryllium	mg/L	0.005	0.005	m ² /s	6.5 × 10 ⁻¹¹	9.0 × 10 ⁻¹¹
Boron	mg/L	0.44	0.50	m ² /s	2.4 × 10 ⁻¹⁰	3.5 × 10 ⁻¹⁰
Cadmium	mg/L	0.0029	0.0045	m ² /s	1.7 × 10 ⁻¹¹	3.1 × 10 ⁻¹¹
Calcium	mg/L	2,139	2,490	m ² /s	2.3 × 10 ⁻⁰⁹	4.5 × 10 ⁻⁰⁹
Chromium	mg/L	0.042	0.14	m ² /s	2.4 × 10 ⁻¹¹	4.3 × 10 ⁻¹¹
Cobalt	mg/L	0.0061	0.0125	m ² /s	3.7 × 10 ⁻¹¹	5.3 × 10 ⁻¹¹
Copper	mg/L	0.13	0.19	m ² /s	1.4 × 10 ⁻¹⁰	1.6 × 10 ⁻¹⁰
Iron	mg/L	0.11	1.6	m ² /s	1.1 × 10 ⁻⁰⁹	2.1 × 10 ⁻⁰⁹
Lead	mg/L	0.11	0.77	m ² /s	1.4 × 10 ⁻⁰⁹	2.8 × 10 ⁻⁰⁹
Lead-210	Bq/L	19	75	m ² /s	3.3 × 10 ⁻¹⁰	3.3 × 10 ⁻¹⁰
Magnesium	mg/L	1.6	1.8	m ² /s	6.3 × 10 ⁻¹⁰	9.9 × 10 ⁻¹⁰
Manganese	mg/L	0.025	0.025	m ² /s	6.8 × 10 ⁻¹¹	9.4 × 10 ⁻¹¹
Mercury	mg/L	0.000038	0.000012	m ² /s	3.5 × 10 ⁻⁰⁹	4.5 × 10 ⁻⁰⁹
Molybdenum	mg/L	230	598	m ² /s	9.1 × 10 ⁻¹⁰	1.8 × 10 ⁻⁰⁹
Nickel	mg/L	0.005	0.035	m ² /s	2.6 × 10 ⁻¹⁰	4.4 × 10 ⁻¹⁰
Polonium-210	Bq/L	3.5	4.2	m ² /s	2.9 × 10 ⁻⁰⁹	2.9 × 10 ⁻⁰⁹
Potassium	mg/L	103	389	m ² /s	1.9 × 10 ⁻¹⁰	3.6 × 10 ⁻¹⁰
Radium-226	Bq/L	276	288	m ² /s	2.9 × 10 ⁻¹⁰	5.3 × 10 ⁻¹⁰
Radium-228	Bq/L	6.6	19	m ² /s	1.8 × 10 ⁻¹⁰	1.8 × 10 ⁻¹⁰

Table 4-1: Primary Stopes Source Terms

Constituent	Units	Advection (Porewater Quality)		Units	Diffusivity	
		Base Case	Upper Case		Base Case	Upper Case
Selenium	mg/L	1.1	1.6	m ² /s	1.2 × 10 ⁻¹⁰	1.3 × 10 ⁻¹⁰
Silver	mg/L	0.0096	0.0195	m ² /s	7.0 × 10 ⁻¹²	1.3 × 10 ⁻¹¹
Sodium	mg/L	3,048	3,267	m ² /s	7.7 × 10 ⁻¹¹	1.5 × 10 ⁻¹⁰
Strontium	mg/L	2.9	3.4	m ² /s	4.4 × 10 ⁻¹⁰	8.1 × 10 ⁻¹⁰
Sulphate	mg/L	12,091	13,837	m ² /s	5.0 × 10 ⁻¹¹	8.7 × 10 ⁻¹¹
Thallium	mg/L	0.0104	0.0125	m ² /s	1.3 × 10 ⁻⁰⁹	2.1 × 10 ⁻⁰⁹
Tin	mg/L	0.005	0.005	m ² /s	6.5 × 10 ⁻¹¹	9.0 × 10 ⁻¹¹
Titanium	mg/L	0.399	1.13	m ² /s	6.8 × 10 ⁻¹⁰	1.4 × 10 ⁻⁰⁹
Uranium	mg/L	0.017	0.123	m ² /s	9.9 × 10 ⁻⁰⁸	2.0 × 10 ⁻⁰⁷
Vanadium	mg/L	0.037	0.050	m ² /s	3.0 × 10 ⁻⁰⁹	5.9 × 10 ⁻⁰⁹
Zinc	mg/L	0.034	0.053	m ² /s	4.6 × 10 ⁻¹⁰	8.2 × 10 ⁻¹⁰

a) Data used in the source term derivation of nitrogen species for advection and diffusion components are based on materials that do not reflect the effects of residual blasting products on the ore chemistry and process plant circuit chemistry. The effect of nitrogen loading from residual blasting products on the mine water system was further assessed and quantified in the site-wide water balance/water quality model (TSD XVIII).

Bq/L = becquerels per litre; n/a = not applicable; N = nitrogen; P = phosphorus; CaCO₃ = calcium carbonate.

4.2 Secondary Stopes Source Terms

Derived source terms for the secondary stopes are provided in Table 4-2 and consist of estimated porewater quality in units of milligrams per litre (mg/L; unless indicated otherwise) and calculated diffusivity in units of m²/s.

Table 4-2: Secondary Stope Source Terms

Constituent	Units	Advection (Porewater Quality)		Units	Diffusivity	
		Base Case	Upper Case		Base Case	Upper Case
pH	pH units	11	12	n/a	n/a	n/a
Alkalinity, as CaCO ₃	mg/L	897	4,220	m ² /s	1.7 × 10 ⁻¹⁰	1.8 × 10 ⁻¹⁰
Ammonia, as N	mg/L	3.2	3.4	m ² /s	3.5 × 10 ⁻¹⁰	3.5 × 10 ⁻¹⁰
Chloride	mg/L	666	699	m ² /s	8.2 × 10 ⁻¹¹	1.6 × 10 ⁻¹⁰
Fluoride	mg/L	5.5	6.2	m ² /s	1.9 × 10 ⁻¹⁰	2.5 × 10 ⁻¹⁰
Nitrite, as N ^(a)	mg/L	0.025	0.025	m ² /s	9.2 × 10 ⁻⁰⁹	9.2 × 10 ⁻⁰⁹
Nitrate, as N ^(a)	mg/L	0.021	0.021	m ² /s	1.5 × 10 ⁻⁰⁷	2.8 × 10 ⁻⁰⁷
Phosphate, as P	mg/L	0.027	0.028	m ² /s	3.6 × 10 ⁻⁰⁸	3.6 × 10 ⁻⁰⁸
Aluminium	mg/L	3.3	24	m ² /s	1.0 × 10 ⁻⁰⁹	1.5 × 10 ⁻⁰⁹
Antimony	mg/L	0.0088	0.0102	m ² /s	1.5 × 10 ⁻⁰⁹	2.9 × 10 ⁻⁰⁹
Arsenic	mg/L	0.64	1.1	m ² /s	1.8 × 10 ⁻¹⁰	3.4 × 10 ⁻¹⁰
Barium	mg/L	0.033	0.072	m ² /s	7.8 × 10 ⁻¹⁰	1.5 × 10 ⁻⁰⁹
Beryllium	mg/L	0.005	0.005	m ² /s	6.5 × 10 ⁻¹¹	9.0 × 10 ⁻¹¹
Boron	mg/L	0.45	0.54	m ² /s	2.4 × 10 ⁻¹⁰	3.5 × 10 ⁻¹⁰
Cadmium	mg/L	0.0027	0.0045	m ² /s	1.7 × 10 ⁻¹¹	3.1 × 10 ⁻¹¹
Calcium	mg/L	2251	2566	m ² /s	2.3 × 10 ⁻⁰⁹	4.5 × 10 ⁻⁰⁹
Chromium	mg/L	0.04	0.23	m ² /s	2.4 × 10 ⁻¹¹	4.3 × 10 ⁻¹¹
Cobalt	mg/L	0.006	0.0174	m ² /s	3.7 × 10 ⁻¹¹	5.3 × 10 ⁻¹¹
Copper	mg/L	0.14	0.21	m ² /s	1.4 × 10 ⁻¹⁰	1.6 × 10 ⁻¹⁰
Iron	mg/L	0.108	1.6	m ² /s	1.1 × 10 ⁻⁰⁹	2.1 × 10 ⁻⁰⁹

Table 4-2: Secondary Stope Source Terms

Constituent	Units	Advection (Porewater Quality)		Units	Diffusivity	
		Base Case	Upper Case		Base Case	Upper Case
Lead	mg/L	0.10	1.4	m ² /s	1.4 × 10 ⁻⁰⁹	2.8 × 10 ⁻⁰⁹
Lead-210	Bq/L	17	72	m ² /s	3.3 × 10 ⁻¹⁰	3.3 × 10 ⁻¹⁰
Magnesium	mg/L	1.8	2.0	m ² /s	6.3 × 10 ⁻¹⁰	9.9 × 10 ⁻¹⁰
Manganese	mg/L	0.024	0.053	m ² /s	6.8 × 10 ⁻¹¹	9.4 × 10 ⁻¹¹
Mercury	mg/L	0.0000063	0.000016	m ² /s	3.5 × 10 ⁻⁰⁹	4.5 × 10 ⁻⁰⁹
Molybdenum	mg/L	218	558	m ² /s	9.1 × 10 ⁻¹⁰	1.8 × 10 ⁻⁰⁹
Nickel	mg/L	0.007	0.068	m ² /s	2.6 × 10 ⁻¹⁰	4.4 × 10 ⁻¹⁰
Polonium-210	Bq/L	3.3	3.9	m ² /s	2.9 × 10 ⁻⁰⁹	2.9 × 10 ⁻⁰⁹
Potassium	mg/L	104	468	m ² /s	1.9 × 10 ⁻¹⁰	3.6 × 10 ⁻¹⁰
Radium-226	Bq/L	257	268	m ² /s	2.9 × 10 ⁻¹⁰	5.3 × 10 ⁻¹⁰
Radium-228	Bq/L	7.1	18	m ² /s	1.8 × 10 ⁻¹⁰	1.8 × 10 ⁻¹⁰
Selenium	mg/L	1.0	1.5	m ² /s	1.2 × 10 ⁻¹⁰	1.3 × 10 ⁻¹⁰
Silver	mg/L	0.0089	0.0184	m ² /s	7.0 × 10 ⁻¹²	1.3 × 10 ⁻¹¹
Sodium	mg/L	2893	3205	m ² /s	7.7 × 10 ⁻¹¹	1.5 × 10 ⁻¹⁰
Strontium	mg/L	2.8	4.0	m ² /s	4.4 × 10 ⁻¹⁰	8.1 × 10 ⁻¹⁰
Sulphate	mg/L	11,764	13,336	m ² /s	5.0 × 10 ⁻¹¹	8.7 × 10 ⁻¹¹
Thallium	mg/L	0.0102	0.0147	m ² /s	1.3 × 10 ⁻⁰⁹	2.1 × 10 ⁻⁰⁹
Tin	mg/L	0.005	0.005	m ² /s	6.5 × 10 ⁻¹¹	9.0 × 10 ⁻¹¹
Titanium	mg/L	0.388	1.07	m ² /s	6.8 × 10 ⁻¹⁰	1.4 × 10 ⁻⁰⁹
Uranium	mg/L	0.017	0.123	m ² /s	9.9 × 10 ⁻⁰⁸	2.0 × 10 ⁻⁰⁷
Vanadium	mg/L	0.057	0.069	m ² /s	3.0 × 10 ⁻⁰⁹	5.9 × 10 ⁻⁰⁹
Zinc	mg/L	0.040	0.114	m ² /s	4.6 × 10 ⁻¹⁰	8.2 × 10 ⁻¹⁰

a) Data used in the source term derivation of nitrogen species for advection and diffusion components are based on materials that do not reflect the effects of residual blasting products on the ore chemistry and process plant circuit chemistry. The effect of nitrogen loading from residual blasting products on the mine water system was further assessed and quantified in the site-wide water balance/water quality model (TSD XVIII).

Bq/L = becquerels per litre; n/a = not applicable; N = nitrogen; P = phosphorus; CaCO₃ = calcium carbonate.

4.3 Underground Tailings Management Facility Source Terms

Derived source terms for the UGTMF are provided in Table 4-3 and consist of estimated porewater quality in units of mg/L (unless indicated otherwise) and calculated diffusivity in units of m²/s.

Table 4-3: Underground Tailings Management Facility Source Terms

Constituent	Units	Advection (Porewater Quality)		Units	Diffusivity	
		Base Case	Upper Case		Base Case	Upper Case
pH	pH units	10	12	n/a	n/a	n/a
Alkalinity, as CaCO ₃	mg/L	349	4,549	m ² /s	8.4 × 10 ⁻¹⁰	1.5 × 10 ⁻⁰⁹
Ammonia, as N	mg/L	2.6	2.6	m ² /s	2.2 × 10 ⁻¹⁰	2.4 × 10 ⁻¹⁰
Chloride	mg/L	287	293	m ² /s	1.3 × 10 ⁻¹⁰	3.3 × 10 ⁻¹⁰
Fluoride	mg/L	3.7	3.8	m ² /s	6.9 × 10 ⁻⁰⁹	9.4 × 10 ⁻⁰⁹
Nitrite, as N ^(a)	mg/L	0.024	0.024	m ² /s	1.4 × 10 ⁻⁰⁸	1.4 × 10 ⁻⁰⁸
Nitrate, as N ^(a)	mg/L	0.023	0.023	m ² /s	1.7 × 10 ⁻⁰⁷	3.7 × 10 ⁻⁰⁷
Phosphate, as P	mg/L	0.026	0.026	m ² /s	1.7 × 10 ⁻⁰⁸	1.7 × 10 ⁻⁰⁸
Aluminum	mg/L	1.4	5.3	m ² /s	2.6 × 10 ⁻⁰⁶	1.4 × 10 ⁻⁰⁴

Table 4-3: Underground Tailings Management Facility Source Terms

Constituent	Units	Advection (Porewater Quality)		Units	Diffusivity	
		Base Case	Upper Case		Base Case	Upper Case
Antimony	mg/L	0.0104	0.0117	m ² /s	7.6 × 10 ⁻⁰⁸	1.2 × 10 ⁻⁰⁷
Arsenic	mg/L	1.7	4.1	m ² /s	2.0 × 10 ⁻¹⁰	8.2 × 10 ⁻⁰⁸
Barium	mg/L	0.051	0.172	m ² /s	2.0 × 10 ⁻⁰⁹	2.2 × 10 ⁻⁰⁸
Beryllium	mg/L	0.004	0.004	m ² /s	5.0 × 10 ⁻⁰⁹	1.4 × 10 ⁻⁰⁸
Boron	mg/L	0.55	0.80	m ² /s	1.3 × 10 ⁻⁰⁹	3.5 × 10 ⁻⁰⁹
Cadmium	mg/L	0.0013	0.0046	m ² /s	5.2 × 10 ⁻¹⁰	1.5 × 10 ⁻⁰⁹
Calcium	mg/L	3,085	3,138	m ² /s	7.6 × 10 ⁻¹⁰	1.2 × 10 ⁻⁰⁹
Chromium	mg/L	0.025	0.88	m ² /s	8.6 × 10 ⁻¹¹	2.5 × 10 ⁻¹⁰
Cobalt	mg/L	0.005	0.0544	m ² /s	1.2 × 10 ⁻⁰⁹	6.7 × 10 ⁻⁰⁹
Copper	mg/L	0.23	0.39	m ² /s	9.8 × 10 ⁻¹⁰	2.2 × 10 ⁻⁰⁹
Iron	mg/L	0.089	1.1	m ² /s	9.0 × 10 ⁻⁰⁸	3.9 × 10 ⁻⁰⁷
Lead	mg/L	0.04	5.8	m ² /s	6.1 × 10 ⁻⁰⁹	2.6 × 10 ⁻⁰⁸
Lead-210	Bq/L	4.6	47	m ² /s	3.9 × 10 ⁻⁰⁹	6.5 × 10 ⁻⁰⁹
Magnesium	mg/L	3.1	3.2	m ² /s	8.7 × 10 ⁻⁰⁹	1.6 × 10 ⁻⁰⁸
Manganese	mg/L	0.020	0.264	m ² /s	5.9 × 10 ⁻⁰⁹	1.4 × 10 ⁻⁰⁸
Mercury	mg/L	0.000026	0.000045	m ² /s	2.4 × 10 ⁻⁰⁹	1.3 × 10 ⁻⁰⁸
Molybdenum	mg/L	133	263	m ² /s	1.2 × 10 ⁻⁰⁹	3.3 × 10 ⁻⁰⁹
Nickel	mg/L	0.02	0.311	m ² /s	5.4 × 10 ⁻¹⁰	4.7 × 10 ⁻⁰⁹
Polonium-210	Bq/L	2.0	2.3	m ² /s	5.2 × 10 ⁻⁰⁸	9.2 × 10 ⁻⁰⁸
Potassium	mg/L	109	1,058	m ² /s	2.8 × 10 ⁻¹⁰	1.3 × 10 ⁻⁰⁹
Radium-226	Bq/L	116	118	m ² /s	6.9 × 10 ⁻⁰⁹	2.1 × 10 ⁻⁰⁸
Radium-228	Bq/L	11	18	m ² /s	1.2 × 10 ⁻¹⁰	1.2 × 10 ⁻¹⁰
Selenium	mg/L	0.45	0.55	m ² /s	1.2 × 10 ⁻¹⁰	1.2 × 10 ⁻⁰⁹
Silver	mg/L	0.0031	0.010	m ² /s	5.2 × 10 ⁻¹¹	1.4 × 10 ⁻¹⁰
Sodium	mg/L	1,728	2,745	m ² /s	2.1 × 10 ⁻¹⁰	1.1 × 10 ⁻⁰⁹
Strontium	mg/L	1.7	8.7	m ² /s	5.7 × 10 ⁻¹⁰	7.5 × 10 ⁻¹⁰
Sulphate	mg/L	9,315	9,577	m ² /s	3.5 × 10 ⁻¹⁰	7.4 × 10 ⁻¹⁰
Thallium	mg/L	0.0092	0.0312	m ² /s	1.2 × 10 ⁻⁰⁹	3.2 × 10 ⁻⁰⁹
Tin	mg/L	0.004	0.004	m ² /s	4.2 × 10 ⁻⁰⁹	1.4 × 10 ⁻⁰⁸
Titanium	mg/L	0.308	0.632	m ² /s	9.3 × 10 ⁻¹⁰	2.4 × 10 ⁻⁰⁹
Uranium	mg/L	0.024	0.126	m ² /s	4.2 × 10 ⁻⁰⁹	2.3 × 10 ⁻⁰⁸
Vanadium	mg/L	0.21	0.21	m ² /s	5.8 × 10 ⁻¹⁰	1.2 × 10 ⁻⁰⁸
Zinc	mg/L	0.089	0.573	m ² /s	8.2 × 10 ⁻⁰⁹	3.7 × 10 ⁻⁰⁸

a) Data used in the source term derivation of nitrogen species for advection and diffusion components are based on materials that do not reflect the effects of residual blasting products on the ore chemistry and process plant circuit chemistry. The effect of nitrogen loading from residual blasting products on the mine water system was further assessed and quantified in the site-wide water balance/water quality model (TSD XVIII).

Bq/L = becquerels per litre; n/a = not applicable; N = nitrogen; P = phosphorus; CaCO₃ = calcium carbonate.

4.4 Discussion

The derived source terms for the primary stopes, secondary stopes, and UGTMF are discussed in the context of the two mass transfer components. Key results of the advection source term components for the three disposal areas are summarized below:

- Estimated drainage chemistries for the primary and secondary stopes are very similar since CPB forms the dominant material type that will be disposed in these mine workings. Drainage chemistry for the UGTMF is different due to the inclusion of the process wastes and lower binder content.
- Estimated drainage chemistries for the underground mine stopes and UGTMF are generally characterized by highly alkaline drainage (i.e., pH greater than 10), sulphate-calcium-sodium ion dominated water, and elevated concentrations of metals and radionuclides.
- Alkalinity and pH are predicted to be higher for the underground mine stopes compared to the UGTMF. This relationship is due to the higher binder content needed for the high-strength CPB in the stopes, compared to the lower strength CPT that will be used to backfill the UGTMF.
- Elevated metal concentrations for the underground mine stopes and UGTMF are noted for aluminum, arsenic, cadmium, chromium, copper, iron, lead, molybdenum, selenium, silver, uranium, and zinc. These metals are elevated due to their presence in the neutralized leached residue and process wastes, as well as their solubility under alkaline drainage conditions. For most of these metals, the estimated concentrations are higher in the UGTMF compared to those of the primary and secondary stopes, except for aluminum, molybdenum, and selenium. The highest concentrations for aluminum, molybdenum, and selenium are estimated for the upper cases of the primary and secondary stopes, which have the highest alkalinity and pH values.
- Elevated concentrations of radium-226 are predicted in the estimated drainage chemistry for underground mine stopes and UGTMF. Estimated concentrations for lead-210, polonium-210, radium-226, and radium-228 are slightly higher in the primary and secondary source terms compared to the UGTMF source terms.

Key results of the diffusion components for all three disposal areas are summarized below:

- Estimated observed diffusivity values are similar for primary and secondary stopes since CPB forms the dominant material type that will be disposed in these mine workings. Observed diffusivity values for the UGTMF are generally much higher due to the inclusion of the process wastes and lower binder content. One exception to this observation is uranium, which has a higher observed diffusivity for the primary and secondary stopes.
- The highest observed diffusivity values are estimated for aluminum, antimony, barium, beryllium, iron, lead, magnesium, manganese, mercury, nitrate, nitrite, phosphate, polonium-210, radium-226, tin, uranium, vanadium, and zinc. In the case of aluminum, antimony, beryllium, cadmium, copper, iron, manganese, radium-226, tin, and zinc, the observed diffusivity values are more than two orders of magnitude higher in the UGTMF compared to those of the primary and secondary stopes.

5 SOURCE TERM UNCERTAINTIES AND VALIDATION

Predicted geochemical source terms are inherently uncertain, and the source terms derived for the mine stopes and UGTMF are subject to uncertainties. In general, results from predictive source term models should be considered as indicating long-term trends instead of providing absolute values (INAP 2009).

Key sources of uncertainty for the mine stopes and UGTMF source terms include the quality and relevance of input data, the representation of hydrogeochemical processes in the conceptual model, the limitations of the chosen modelling methods, and the estimation of mineral weathering rates. To reduce the effect of these uncertainties, conservative bounding arguments (e.g., constant source terms and initial mass transfer rates) were intentionally used in the source term derivation. These bounding arguments result in an overestimation of mass transfer rates and water quality predictions, and are expected to be sufficiently conservative to account for the uncertainties.

Furthermore, the proposed long-term disposal of tailings and process wastes in underground workings is a new concept in the Canadian uranium mining industry. Although the use of uranium tailings in CPB technology is not a new concept, the combination of process waste with cemented backfill and the use of an underground disposal strategy is new and unprecedented.

A literature review of published national and international documentation was conducted to find potential analogue sites where this type of uranium tailings and process waste management strategy was used. The literature review specifically targeted publicly available information on the geotechnical, geochemical, and radiological properties of CPB/CPT, disposal methods, and monitored drainage chemistry.

The literature review was conducted using Golder's internal literature database and external databases. Key components to the literature review included the following:

- Golder's technical literature tool, which is a component of an EBSCO information services subscription, was used to search for academic journal articles. The tool links to Golder's external journal subscriptions plus over 10,000 external databases that include various content providers (e.g., ScienceDirect and JSTOR). The tool also includes access to subscription databases such as Environment Complete, Sustainability Reference Center, and Energy & Power Source Complete. For any results in which Golder did not have full text access, a general search on Google and Google Scholar was conducted.
- A web-based search was also conducted for relevant articles and reports published by multinational organizations. These organizations include the Canadian Nuclear Safety Commission, International Atomic Energy Agency, South Africa Water Research Commission, and United States Department of Energy.
- Specific searches were conducted for publicly available data for known active and legacy uranium mines located in Australia (McArthur Basin), Canada (Athabasca Basin, and Bancroft and Elliot Lake areas), Germany (Erzgebirge Ore Mountain), Kazakhstan (Chu-Sarysu, Northern), Namibia (Rössing Mine) and South Africa (Witwatersrand Gold Basin).

The literature review was initially conducted using broad keywords (e.g., CPB, CPT, uranium, and UGTMF) to gain a general understanding of the relevant publicly available literature. Scientific journal articles and technical documents that matched the keyword searches were thoroughly reviewed and assessed for their applicability to the Project. The search was then refined to search for specific locations where CPB and/or CPT may be

produced and disposed underground. This general approach was conducted for each of the three main search tools listed above.

Results from the literature search reinforced the notion that cemented tailings technology from uranium mine sites is not a new technology and studies have been conducted to examine the applicability of storing cemented uranium tailings underground. Academic articles were available that documented the geotechnical properties of cemented backfill (i.e., material strength and hydraulic conductivity) produced from uranium tailings. For example, uniaxial compressive strength results for CPB samples are generally consistent with results for the tailings characterization program conducted for the Project (i.e., 0.5 to 1.5 megapascals using 4% to 6% OPC binder [Panchal et al. 2018]). Literature related to the disposal of CPT plus process wastes in underground mine workings were limited and an appropriate analogue site and or data was not found.

The literature search did not find documentation for water quality predictions or measured data related to leachable concentrations of constituents from CPB or CPT material produced from uranium tailings. Documents that did comment on geochemical properties were restricted to results related to the cemented material pH or the mineralogical characteristics of cemented material. No publicly available information was found that indicates that current uranium mining operations plan to cement and store their tailings and process wastes underground. Research on specific mines in Canada (e.g., Denison, Gunnar Mill, and Madawaska) documented the use of CPB, but water quality data and/or predictions were not available. The Jabiluka Uranium Mining Project in Australia also proposed to store cemented tailings underground; however, it was ultimately determined that this site would not be mined. Validation of the underground tailings and process waste source terms using suitable analogue sites or data is therefore not possible at this stage of the Project.

6 KEY FINDINGS

This technical support document to the EIS presents the methods and assumptions used to generate source term predictions for the disposal of tailings and process wastes in the underground mine stopes and UGTMF. Key findings from source term development are as follows:

- CPB and CPT will be disposed in the underground workings and these composite wastes consist of a combination of neutralized leach residue, process wastes, and cement binder. The geotechnical, geochemical, and radiological properties of these materials were determined through an extensive characterization process.
- The CPB and CPT materials primarily consist of the acid resistant minerals from the ore, have low hydraulic conductivity, are classified as non-potentially acid generating, and have alkaline leachable fractions of solutes and radionuclides. The CPB will be disposed in the primary and secondary mine stopes and used for plugging and capping of the disposal chambers of the UGTMF. The CPT will be disposed in the UGTMF.
- The release of solutes from CPB and CPT during Operations is not expected since no residual water is expected to be generated from the backfilled materials. Post-closure re-flooding of the mine will inundate the CPB and CPT disposal areas and two mass transfer mechanisms (i.e., advection and diffusion) will result in the release of constituents to the surrounding groundwater.
- Source term models were developed for the primary stopes, secondary stopes, and UGTMF. Individual source terms consist of two mass transfer components that are simulated using an engineering modelling approach supported by a purposely designed characterization program with empirical laboratory

measurements of key mass transfer processes. Source terms were developed to represent a range of binder strengths to account for an envelope of potential operating conditions.

- Given the complexity of the physical and chemical processes that determine the magnitude and rate of advective and diffusive mass transfer from the underground mine stopes and UGTMF, simplifying assumptions were used in the source term models to reduce the necessary parameters and/or variables to those that can be measured using applicable laboratory tests. Additional bounding arguments were made to establish a conservative case for the mine stopes and UGTMF source terms that intentionally overestimate the mass loading from these disposal areas. Specifically, source terms were developed assuming that mass transfer rates of constituents from the underground workings will be constant over time and leaching rates and leachate qualities are equivalent to peak values measured from the characterization program.
- The advection source term components for the underground mine stopes and UGTMF indicate that the drainage chemistries for the primary and secondary stopes are very similar due to the same CPB material and different to the UGTMF due to the inclusion of the process wastes and lower binder contents in the CPT.
- Estimated drainage chemistries are characterized by highly alkaline drainage (i.e., pH greater than 10), sulphate-calcium-sodium dominated water, and elevated metals and radionuclides. Elevated metal concentrations are noted for aluminum, arsenic, cadmium, chromium, copper, iron, lead, molybdenum, selenium, silver, uranium, zinc, radium-226, and lead-210.
- Estimated observed diffusivity values are similar for primary and secondary stopes and higher for UGTMF due to the inclusion of the process wastes and lower binder contents. One exception to this observation is uranium, which has a higher observed diffusivity for the primary and secondary stopes. The highest observed diffusivity values are noted for aluminum, antimony, barium, beryllium, iron, lead, magnesium, manganese, mercury, nitrate, nitrite, phosphate, polonium-210, radium-226, tin, uranium, vanadium, and zinc.
- Validation of the source term predictions are not possible due to a lack of suitable analogue sites or publicly available analogue data. As a result, the source terms were developed to be sufficiently conservative to account for input uncertainties as understood at the time of modelling. It is expected that further refinement and modification of the source terms will be conducted as further characterization, testing, and monitoring data become available.
- The source term predictions were used as input data in the groundwater solute transport model to evaluate the combined solute mass loading from waste disposal facilities (i.e., underground workings and waste rock disposal areas) to downgradient receptors. The reader is referred to the hydrogeology section of the EIS (Section 8) for more information on the application of these source term predictions.

CLOSING

Golder is pleased to submit this report to NexGen in support of the environmental assessment for the Rook I Project. For details on the limitations and use of information presented in this report, please refer to the Study Limitations section following this page. If you have any questions or require additional details related to this study, please contact the undersigned.

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