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Coordinated landform and multi-layer gas barrier cover system design for uranium tailings

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Abstract

During the late 1950s to early 1980s, historic operations at a former uranium mine and mill site in Canada resulted in the deposition of about 5 million tonnes of uranium tailings into two tailings management areas (TMAs). In the 1980s, the site was rehabilitated to the standards of the day, which included placement of a simple cover system consisting of a single 0.3–0.5 m thick layer of sand and gravel over the tailings.

The authors, as part of a project team, evaluated the performance of the past decommissioning efforts relative to current regulatory standards and recommended that the TMA cover system be upgraded to better control surface erosion, reduce the emission of radon gas, and limit water infiltration into the tailings as part of the progressive rehabilitation of the former mine site. A multi-layer cover including a sand-gravel-bentonite (SGB) layer was selected to upgrade the soil cover of the TMAs to limit migration of radon gas from the tailings. This type of diffusion barrier cover system incorporates a 'performance' layer of sand and gravel amended with bentonite and a 'protective' layer of sand and gravel above the performance layer. Performance, in terms of reducing radon diffusion, is attained through sustained saturation of the performance layer by providing water retention in the protective layer. This type of cover system has typically been installed on relatively flat grades because infiltration of precipitation into the cover is a contributing factor to successful cover performance.

A parallel objective of the rehabilitation of the TMAs is to provide a passive closure landform that requires limited maintenance and monitoring over the longer term. A robust landform and drainage system has been designed to control the flow of water and eliminate ponding on the TMAs with the objective of maintaining long-term physical stability while reducing maintenance and monitoring requirements. Through improved landform/drainage design, the following are expected to be achieved: (1) long-term physical stability of cover surface, (2) reduced infiltration into the tailings and loading of contaminants to the downstream environment, and (3) containment of clean runoff from the TMAs within an excavated aggregate/infiltration area with conveyance of flow to the subsurface (i.e. no surface discharge). The landform design for the TMAs includes surface slopes of up to 10H:1V.

Upgrading of the cover system commenced in 2015 and was completed on TMA-2 in 2017. Performance monitoring of the completed upgraded cover has been ongoing since 2017, including measurement of saturation levels, suction pressures and temperature within the cover, radon flux from the surface of the cover and visual inspection of the cover surface for signs of erosion and slope instability. Monitoring results have indicated that design objectives are being met or exceeded and the performance of the cover, in terms of internal cover saturation levels, is being achieved on slopes of up to 10H:1V. These results demonstrate that landform/drainage design that allows for shedding of clean surface waters can be achieved while maintaining adequate saturation levels within the diffusion barrier cover.

Keywords: *tailings cover, radon, landform, closure drainage, uranium*

1 Introduction

During the late 1950s to early 1980s, historic operations at a former uranium mine and mill site in Canada resulted in the deposition of about 5 million tonnes of uranium tailings into two tailings management areas (TMAs). Ore extracted from the mine was transported to surface where it was milled and beneficiated on site. Uranium ore beneficiation consisted of crushing, grinding, leaching, filtration, and hydrometallurgical processing, with a milling capacity of about 750 tonnes per operating day. After 1982, limited decommissioning activities were initiated at the site, including demolition of buildings and infrastructure, securing mine openings to surface, vegetation of disturbed areas, and covering the surfaces of the TMAs with a 0.3–0.5 m thick layer of sand and gravel.

In the early 2000s, an evaluation of the performance of the past decommissioning efforts relative to current regulatory standards was completed. This evaluation recommended that the TMA cover system be upgraded to better control surface erosion, reduce the emission of radon gas, and limit water infiltration into the tailings. The need for a drainage outlet was also identified at Tailings Management Area No. 2 (TMA-2) to eliminate potential for overtopping of the containment structure.

Progressive rehabilitation was initiated at the site in 2015. Grading, covering and drainage outlet construction at TMA-2 was completed in 2017 and monitoring has been ongoing since completion. This paper presents a case study of the coordinated design, construction and performance monitoring of soil cover and water management system for TMA-2.

2 Rehabilitation objectives

2.1 Site conditions

The former uranium mine site is in Canada and, on average, receives total precipitation of approximately 900 mm per year, of which about 30% falls as snow between November and March. Evaporation occurs mostly between April and October, with an average annual potential evaporation rate of approximately 580 mm over open water. The average air temperatures are −7.5°C between December and March and 17.4°C between June and August.

TMA-2 has a surface drainage area of approximately 26 ha. The drainage area is bounded by a bedrock outcrop to the north, a waste rock embankment to the east and south, and a perimeter berm to the west. The pre-rehabilitation surface of TMA-2 was sloped from west to east, with water collecting in a low-lying area adjacent to the waste rock embankment. Under this condition, there was no surface drainage outlet from TMA-2. Water collected would pond seasonally before evaporating and/or infiltrating through the tailings into the subsurface. Overtopping of the waste rock embankment was possible during an extreme rainfall/snowmelt event; therefore, it was recommended that an outlet be provided to prevent such an occurrence.

2.2 Physical stability

The primary concern related to physical stability of the pre-rehabilitated TMA-2 was the absence of a drainage outlet and associated potential for water accumulation resulting in an overtopping of the waste rock embankment. To address this concern, an outlet was designed in combination with a landform design for the surface of TMA-2 to limit surface erosion over the long term. The rehabilitation design objectives for TMA-2 related to physical stability were:

- Provide long-term physical stability of the TMA surface against erosion.
- Maintain or improve the physical stability of the waste rock embankment structure.
- Provide positive drainage conditions that eliminate the potential for overtopping of the waste rock embankment structure.
- Reduce infiltration into the tailings.

2.3 Chemical stability

The mineralogy of the tailings primarily consists of silicate minerals with lesser amounts of carbonate, sulfate, sulfide, various oxides and uranium minerals. The tailings were determined to be non-acid generating with excess neutralising potential. Primarily, uranium radioisotopes and radium-226 are present in the tailings in soluble and leachable forms.

Uranium is continually decaying into other radioisotopes, called progeny or daughters. For instance, radon (Rn-222), a radioactive gaseous element with a half-life of 3.8 days, is produced from the decay of radium (Ra-226), which in turn is a daughter of uranium (U-238). The emission of radon gas from the tailings was identified as a potential risk to the public and the environment, due to the presence of Ra-226 (Junqueira et al. 2016).

The objective related to radon emission from TMAs was to reduce the radon concentrations in the air to meet the Canadian-regulated non-nuclear energy worker dose limits and/or to align with the 'as low as reasonably achievable' principle at locations beyond the site property limits. Radon dispersion modelling determined that a 93%, or more, overall reduction in the radon emission rate from the surfaces of the TMAs would satisfy this objective.

3 Landform design

3.1 Surface topography design

The Revised Universal Soil Loss Equation for Application in Canada (RUSLEFAC) (Wall et al. 2002) was used to evaluate the potential for soil loss due to water erosion and support design of the TMA surface topography. The RUSLEFAC is a modified version of the Universal Soil Loss Equation (USLE) developed by the United States Department of Agriculture.

The USLE is an empirical equation used to predict the long-term erosion rates on slopes based on the site-specific rainfall pattern, soil type, topography, vegetation, and soil/erosion management practices (Wall et al. 2002). Erosion rates estimated by the USLE were evaluated using a qualitative ranking system based on soil loss tolerance.

The RUSLEFAC was applied in design by limiting the estimated soil loss over the TMA surface to a 'low' classification, representing an estimated soil loss rate of between 6 and 11 tonnes/hectare/year, without consideration of erosion control measures. A relationship between maximum permissible overland flow path length and surface slope was developed and applied to ensure estimated soil loss rate remained in the 'low' classification over the entire TMA surface. A maximum permissible surface slope of 10H:1V was adopted, corresponding to a maximum permissible overland flow path length of 100 m.

The rehabilitated surface landform design for TMA-2 is shown in Figure 1Figure. TMA-2 was graded towards a main drainage channel that discharges into an aggregate pit external to the TMA that serves as an infiltration gallery. The main drainage channel was excavated through the western perimeter berm, providing an outlet from the TMA and preventing the possibility of overtopping of the waste rock embankment. The main drainage channel has a longitudinal slope of about between 0% and 0.3%, a bottom width between 3 m and 4 m and side slopes of 4(H):1(V) or flatter.

A secondary drainage system, comprising ridges and drainage swales, was designed for the TMA-2 surface upstream of the main drainage channel. This secondary drainage system controls runoff over the TMA surface and reduces the potential for rill and gully erosion by limiting non-channelised overland flow. Flows are directed to the secondary drainage swales, where granular materials will be placed for erosion resistance. The design for TMA-2 includes three drainage swales with longitudinal slopes between 3.5% and 2.5%.

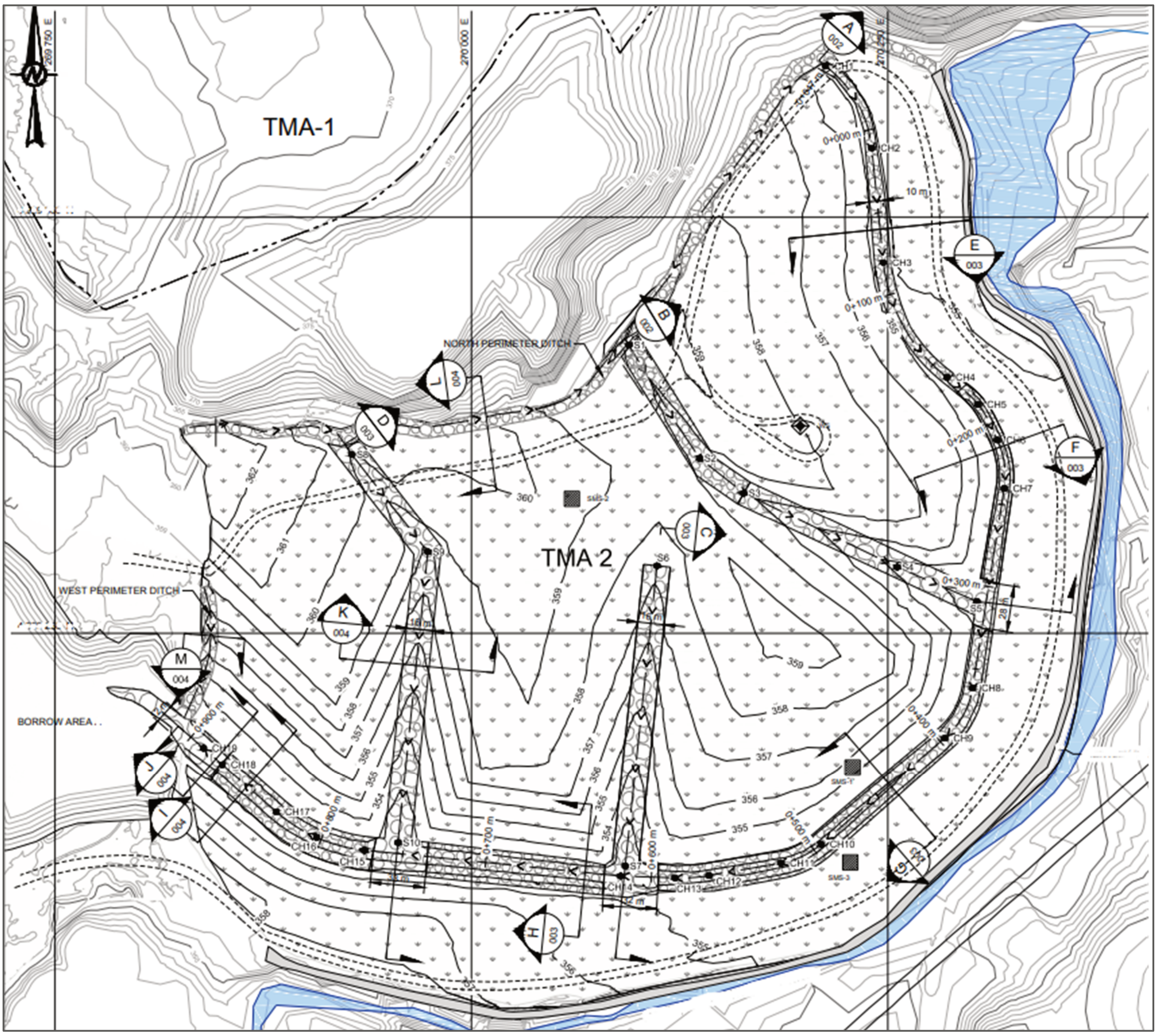

Figure 1 TMA-2 drainage and grading – as-built condition

The soil erosion class for exposed soils over the TMA surface was estimated by the RUSLEFAC to range from very low to low without additional erosion mitigation. Select aggregate material with at least 25% gravel sized particle (by mass) was placed over areas with slopes exceeding 1%. After final grading, the TMA was hydroseeded with a mixture of native grass and mulch. Fertiliser has been applied to the surface annually in the spring since 2017 to help establish vegetation.

Runoff from TMA-2 is conveyed by the outlet channel to a depleted aggregate pit that was used to supply construction material. An overflow outlet is provided from the aggregate pit to prevent overtopping of the TMA-2 waste rock embankment structure. The storage capacity of the aggregate pit below the invert of the overflow outlet exceeds the estimated 100-yr return period runoff volume. Therefore, runoff from the rehabilitated TMA is contained and infiltrates into the subsurface under all but extreme hydrologic conditions.

3.2 Drainage channel design

The drainage system and outlet from TMA-2 were sized to safely pass a design storm event equal to a 1,000-year return period flood. The 1,000-year return period 6-hr duration total rainfall depth was estimated to be 118 mm at the site location. A 'Chicago Storm' distribution hyetograph with 10-min time step was assumed to characterise the temporal variability in rainfall intensity over the duration of the storm event.

The time step of 10 min was selected based on the estimated collection time of the TMA-2 drainage area. The estimated peak 10-min rainfall intensity of 159 mm/hr was assumed for design.

Design flows were estimated using the Hydrologic Engineering Center Hydrologic Modeling System software (HEC-HMS). A peak flow of 5 m^3/s was estimated at the outlet of the TMA. In the main drainage channel, the maximum estimated water depth varies between 0.5 m and 0.8 m, and estimated flow velocities range from 0.8 m/s to 1.0 m/s. In the swales, the maximum water depth is estimated to be about between 0.1 m and 0.2 m and estimated flow velocities range from 1.0 m/s to 1.3 m/s.

A 0.3 m thick layer of larger granular material (i.e. rip-rap), with median diameter ranging from 25 mm to 100 mm was placed along the bed and side slopes of the main channel and swales for erosion protection underlain by a 0.2 m thick well-graded granular filter layer.

4 Multi-layer soil cover design

Several options were considered to address radon emission from the TMAs and a multi-layer soil cover system was identified as the preferred mitigation strategy. When the soil cover is applied, radon gas emitted from the tailings particles must travel through the network of saturated pore spaces in the cover prior to atmospheric release. As the radon travels through the subsurface network of pore spaces in the cover, the radon in part decays into its less harmful progeny due to its relatively short half-life of 3.8 days. Increasing the length of the transport pathways between the source term and the atmosphere and/or increasing the tortuosity of the transport pathways increases the residence time of the radon in the subsurface and allows for further decay of radon into its progeny and sorb to soil particles prior to atmospheric release.

4.1 Diffusion cover

Multi-layer covers with a saturated ‘performance’ layer are designed to limit gas migration to a diffusive flux through a performance layer. These diffusion barrier cover systems are commonly applied in the mining industry to reduce oxygen migration into sulfide tailings. The diffusion coefficient of many gases, including oxygen as well as radon, decreases with the degree of water saturation in a soil, particularly once the saturation levels reach about 85% or greater and interconnected air-filled pore spaces have been occluded or blocked with water. As a result, the rate of radon diffusion through a material can be significantly reduced by maintaining a high degree of water saturation in the performance layer of the soil cover.

A pilot-scale study was completed to test four different soil cover configurations at TMA-2. The cover configurations tested by field test pad were:

- A single-layer 3.3 m thick granular soil cover.
- A 0.5 m thick layer of compacted granular soil amended with 10% sodium bentonite by mass, overlain by 1 m of granular material.
- A 0.4 m thick layer of compacted fine-grain soil, overlain by 1 m of granular material.
- A linear low-density polyethylene membrane overlain by 0.2 m compacted granular soil, amended with 10% sodium bentonite by mass, overlain by 1 m of granular material.

The test pads were monitored to assess the performance of the selected configurations at mitigating the release of radon. A multi-layer cover system with a low permeability performance layer constructed of sand-gravel-bentonite (SGB) with a granular protective cover was selected as the preferred cover option (Junqueira et al. 2016).

The average radon flux rate from pre-rehabilitated TMA-2 surface was estimated to be about 4.3 $Bq/m^2/s$ based on measurements. A 93% reduction in average radon flux from TMA-2 is equivalent to an average permissible radon flux of approximately 0.3 $Bq/m^2/s$.

To evaluate the required degree of cover saturation, radon flux values were calculated using the analytical method presented in Rogers et al. (1984) and validated against the test pad monitoring results.

The theoretical radon flux through the different cover geometries evaluated is shown in Figure 2, which demonstrates how radon flux is expected to vary with saturation levels within the soil cover.

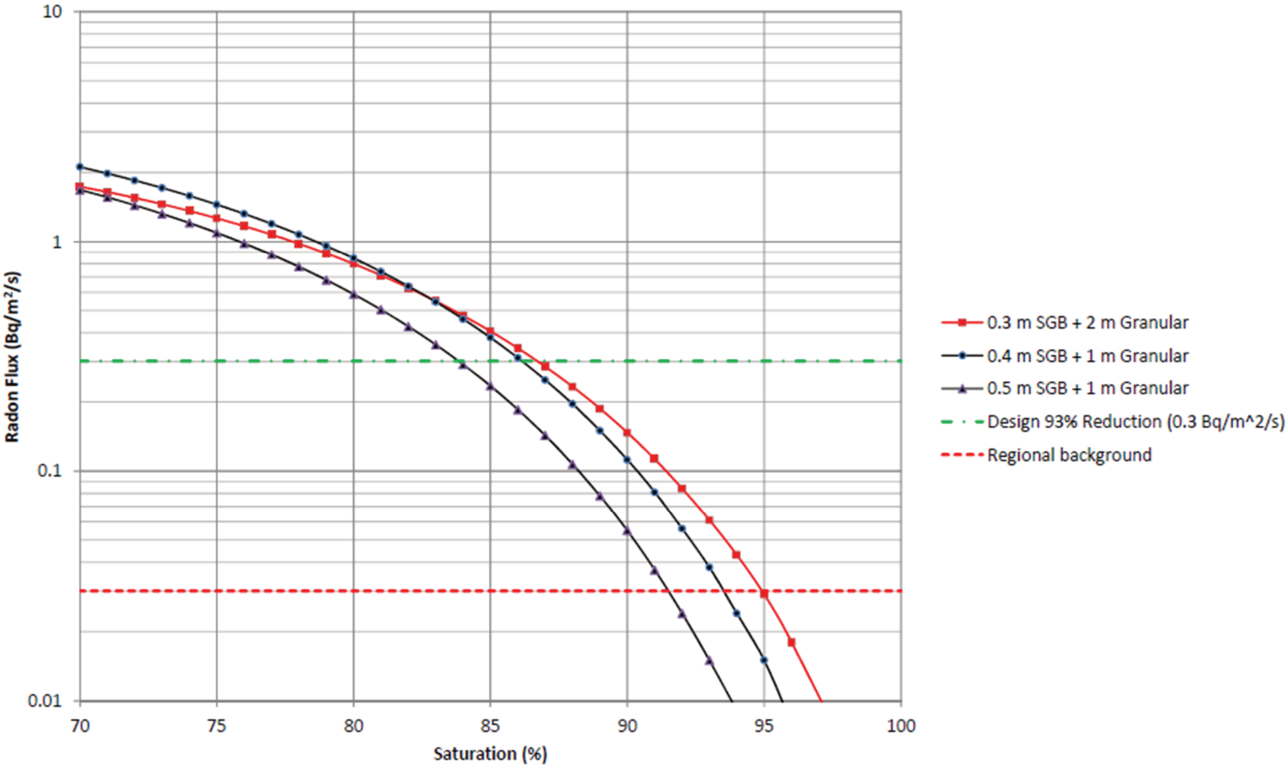

Figure 2 Modelled radon flux and saturation relationship for different sand-gravel-bentonite cover configurations

Figure 2 shows that to achieve an average radon flux of 0.3 Bq/m^2/s, saturation in the SGB should be maintained above a range of 84% to 87% depending on cover profile design.

4.2 Saturation modelling

Numerical simulations were completed to assess the range of saturation that would be expected to exist within the SGB layer given climatic variability over the longer term. Transient models were prepared using a 5-year climate dataset compiled from onsite weather station data. The dataset included daily precipitation, air temperature, relative humidity values, and potential evaporation that estimated using the Thornthwaite method. In addition, long-term precipitation data was obtained from a nearby Environment Canada meteorological station and analysed to estimate rainfall quantity and distribution during a dry season with a 1-in-100-year return period (i.e. a 1% probability of occurrence each year). A sensitivity case was evaluated by including precipitation equal to the 100-year return period dry year in the middle of the 5-year climate dataset. The lower boundary condition of the models was defined as a watertable located either 1 m or 10 m below the base of the cover, the range expected within TMA-2.

The hydraulic properties of the granular protective layer and 10% SGB performance layer materials were based on laboratory measurements. The hydraulic conductivity values of the granular and SGB layers were defined as 1x10^{-4} m/s and 1x10^{-10} m/s, respectively.

The predicted saturation within the SGB layer for the 100-year dry year sensitivity case is presented in Figure 3. The model results indicated that, for typical climatic conditions, the SGB layer underneath 1 m of granular material should maintain saturation levels at or above 92% in areas with a shallow (i.e. 1 m below ground surface) watertable during all times, and saturation could temporarily reduce to about 82% during summer in areas with a deep (i.e. 10 m below ground surface) watertable. The models also indicated that seasonal re-saturation is expected to occur, and that variation in saturation values was slightly greater for the 0.4 m thick SGB layer compared to the 0.5 m thick layer.

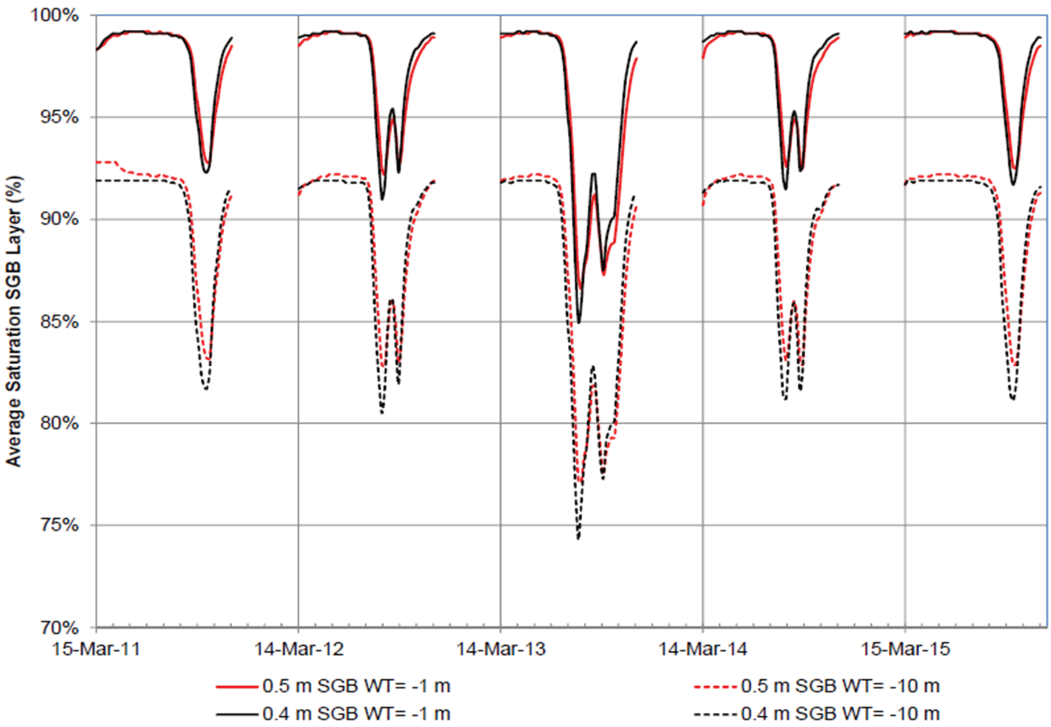

Figure 3 Predicted average saturation in sand-gravel-bentonite layers with 1 m granular cover and 100-year dry condition

During an extreme dry year (100-year dry), saturation within the 0.4 to 0.5 m thick SGB layer could reduce temporarily to values between 75% and 85%, for deep and shallow watertable conditions, respectively. Nevertheless, the 100-year dry event would be short-lived and the saturation levels within the SGB layer were predicted to increase back to values above 90% after climatic conditions return to historic averages.

A 0.4 m thick SGB layer was determined to meet the design criterion during typical climate conditions, with short-lived occurrences of saturation levels below the criterion during extreme dry years.

4.3 Commentary on coordinated landform-diffusion cover design

Soil covers that rely on high saturation are typically applied to low surface gradient tailings deposits that do not promote surface runoff. The landform design objective of providing free-draining, water-shedding conditions is contrary to the requirements of a diffusion cover system to maintain a high degree of saturation, which typically relies on high infiltration (and thereby low runoff). The coordinated design of a diffusion cover system over a closure landform that promotes runoff and water-shedding conditions is somewhat novel within the mine closure industry. The performance of the TMA-2 cover system over closure landform slopes of up to 10H:1V may provide the basis for expanding the utility of saturated diffusion barrier type covers with free-draining landforms.

5 Construction

The TMA-2 cover and drainage system was constructed between 2015 and 2017. Figure 4 illustrates the various phases of landform and cover construction. Construction began with regrading of the existing tailings surface to achieve the topography prescribed by the landform design. SGB was produced by mechanical mixing using a pug mill to an average bentonite content of 10.4%. Produced SGB that met specifications was placed and compacted to an average thickness of 0.41 m. The SGB was mixed to an average water content of 13.2% and placed at an average water content of 12.4%.

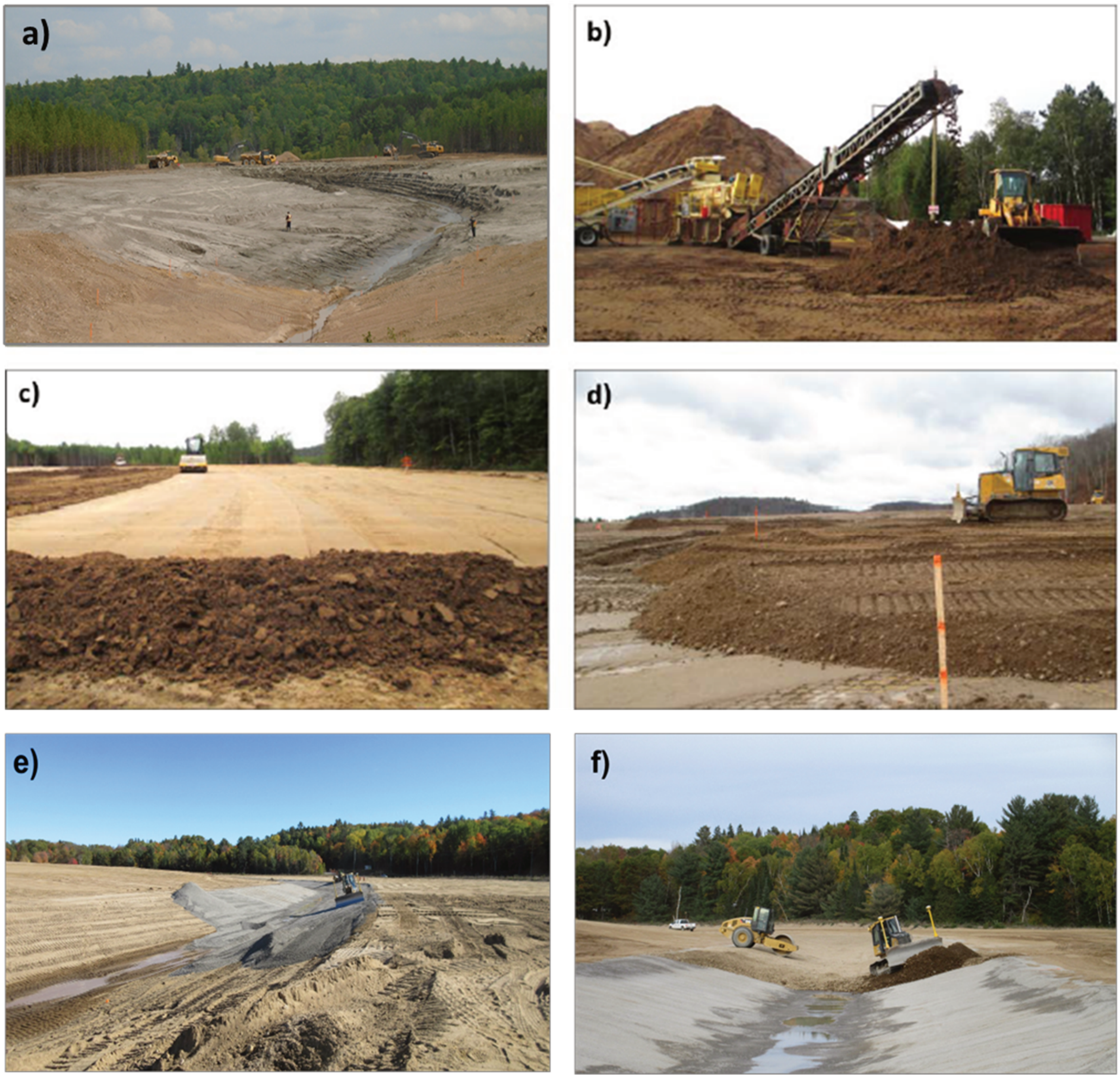

Figure 4 Photos of cover construction: (a) Regrading of tailing to achieve drainage; (b) Pug mill operation producing sand-gravel-bentonite (SGB); (c) Compaction of SGB over prepared tailings subgrade; (d) Placement of granular protective layer; (e) Placement of granular filter material in drainage channel; (f) Placement of larger granular material in drainage channel

In situ hydraulic conductivity tests were carried out with a Guelph permeameter in the SGB layer. The measured in situ hydraulic conductivity typically ranged from 4.3×10^{-9} m/s to 2.2×10^{-11} m/s, with an average of 1.3×10^{-9}.

The SGB layer was covered with a minimum of 1 m of sand and gravel from an onsite aggregate pit with a gradation range of d_{15} = 0.2 to 0.45 mm, d_{50} = 0.5 to 2 mm and d_{85} = 2 to 25 mm. Where drainage channels were located, larger granular material underlain by granular filter bedding was incorporated into this protective cover layer.

6 Performance monitoring

The TMA-2 cover and drainage system are subject to an annual performance monitoring program that includes:

- Review of data from instrumentation installed in situ within the cover.

- Measurement of direct radon flux from the cover surface.
- Physical stability inspections.

6.1 In situ cover monitoring data

There are three soil monitoring stations (SMS) installed within the TMA-2 cover that capture a range of anticipated drainage conditions, as follows:

- SMS-1 is located on a 10H:1V slope to the north of the main drainage channel and the east of the central swale.
- SMS-2 is located near the top of a topographic ridge between the central and western swale.
- SMS-3 is located on a 1% slope between the main drainage channel and the waste rock embankment.

The SMS have instrumentation that measure moisture, suction and temperature at various locations within and below the cover. This paper focuses on presentation of moisture data as it relates to the discussion on coordinated landform-cover design and landform design objectives' influence on cover performance in terms of maintaining sufficient saturation. Results are presented only for stations SMS-1 and SMS-2 because these are positioned at locations where topography and drainage conditions promote runoff and discourage infiltration.

6.1.1 SMS-1 – 10H:1V slope

Variation in moisture content within the cover at SMS-1 is presented in Figure 5 with precipitation. Three of the four moisture sensors installed in the SGB between 0.15 m and 0.25 m above the tailings (i.e. M2, M3 and M5) have shown volumetric water contents at or above 0.3 m^3/m^3, indicating that the SGB layer has maintained high saturation values as intended. Sensor M1, installed in tailings 0.25 m below SGB, has shown fluctuation in values associated with seasonal precipitation, but water content values appear to be decreasing slightly with time. Sensor M6, installed in the 'protective' granular layer 0.75 m above tailings (i.e. base of cover), shows high variation in water content values associated with quick surface infiltration (i.e. recharge) during rainfall events followed by ongoing drainage.

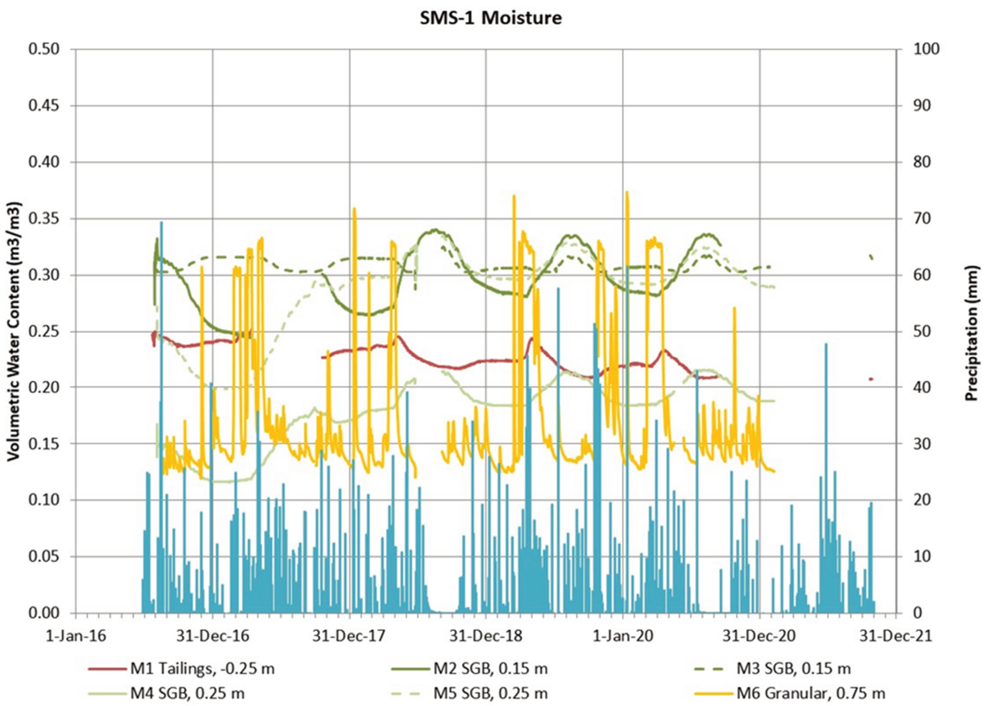

Figure 5 Variation in moisture content – soil monitoring station (SMS)-1; located on 10H:1V slope

6.1.2 SMS-2 – high elevation, near top of topographic ridge

Variation in moisture content within the cover at SMS-2 is presented in Figure 6 with precipitation. All sensors installed in SGB have been measuring water content values that indicate high saturation is sustained in the SGB. Volumetric water content has been measured between 0.26 and 0.36 m^3/m^3 since installation. Sensor M3 has shown an increasing trend in water content values.

Sensor M1, installed in the subgrade 0.3 m below SGB, has shown a progressive decrease in water content from 0.25 m^3/m^3 to below 0.15 m^3/m^3. The fact that water content in this layer has not increased or responded to seasonal precipitation indicates that the SGB layer above is limiting water percolation, as intended in the design. Low infiltration rates in the upper portion of the SGB layer may also explain why moisture sensors M2 and M3, installed in the lower portion of SGB, have shown lower volumetric water content values compared to sensors M4 and M5, which are installed in the upper portion of the SGB layer.

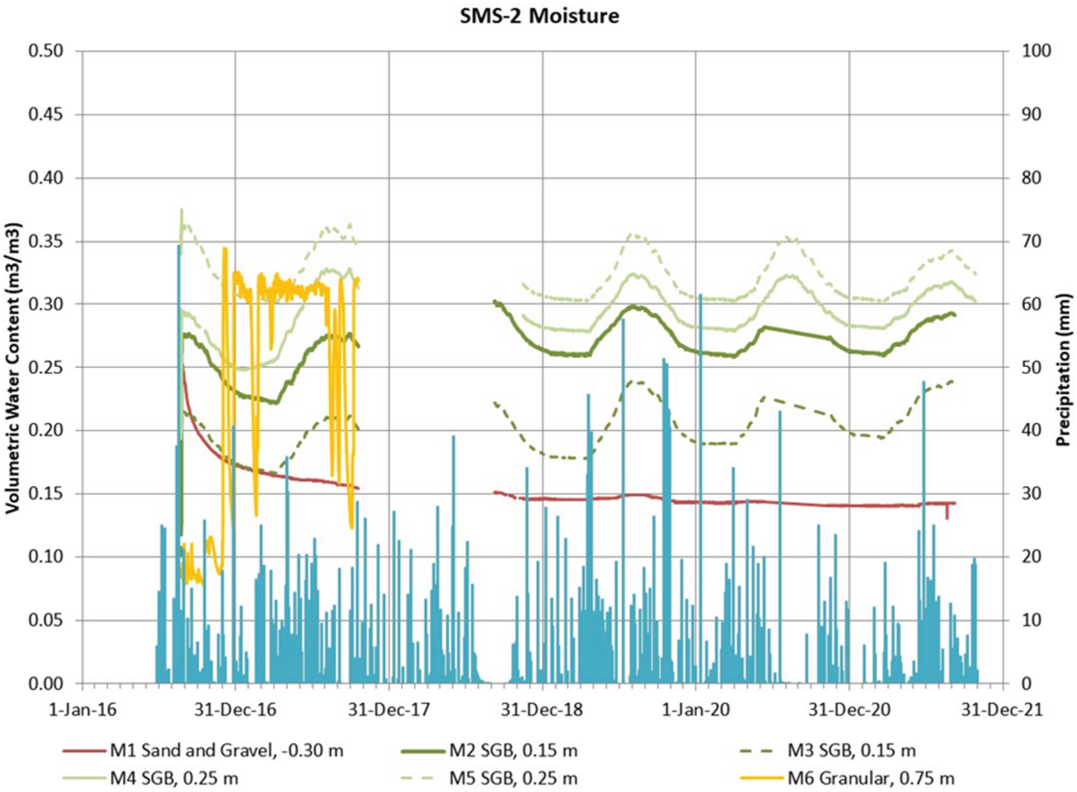

Figure 6 Variation in moisture content – soil monitoring station (SMS)-2; located on topographic ridge

6.2 Radon flux

Radon flux measurements have been collected regularly in the late summer since construction was completed. Monitoring locations were selected to be representative of conditions over the entire TMA. Measurements were collected over a 5-day period, typically in August or early September, when conditions tend to be dry and cover saturation levels would be expected to be at seasonal lows. Measurement was completed by placing activated charcoal into plastic containers coupled to the ground surface to trap emanating gas. The radon emanating from the ground was collected for a nominal period of 24 hours. The charcoal samples were retrieved and analysed for radon concentration. The results are presented in Figure 7 (note the y axis is presented in log scale) with comparison to uncovered tailings and local background concentrations. The average radon flux has been measured to be consistently around 0.02 $Bq/m^2/s$, significantly exceeding the design objective of 0.3 $Bq/m^2/s$.

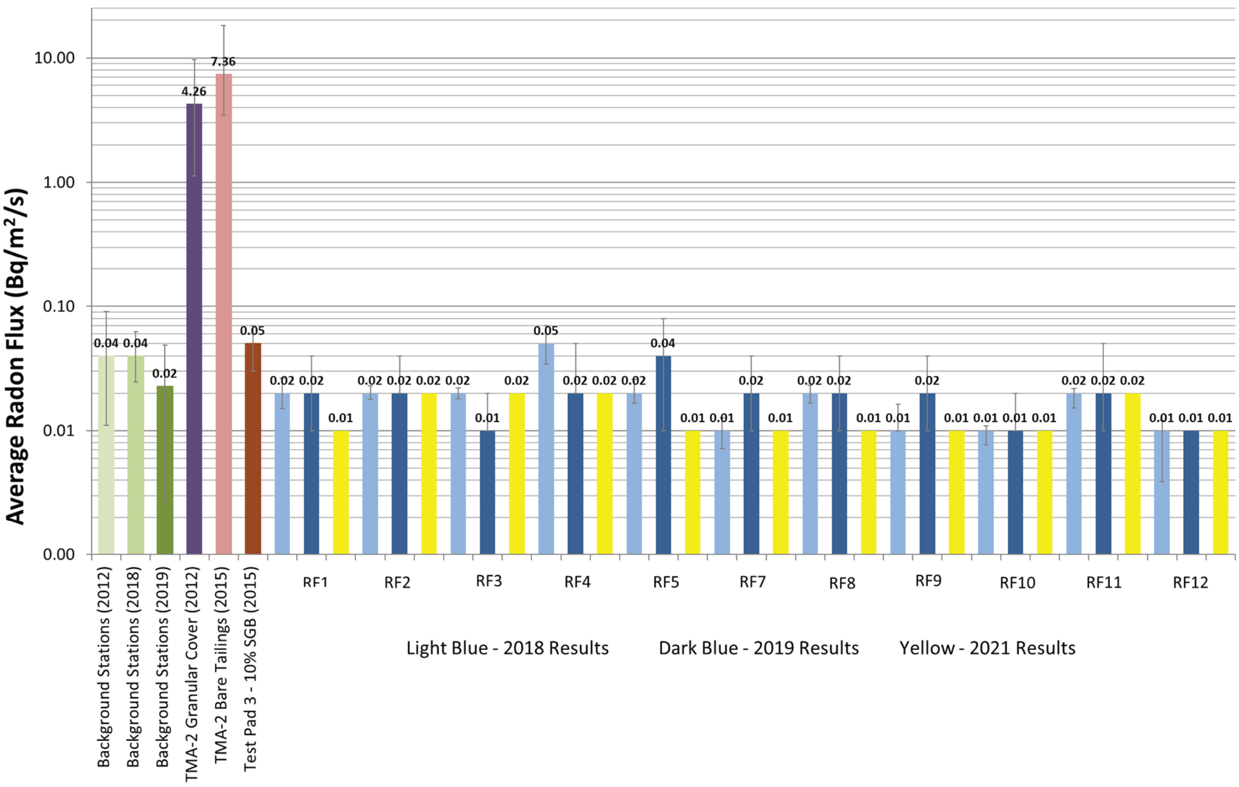

Figure 7 Radon flux measurements

6.3 Physical stability

The TMA-2 cover and drainage system is inspected annually by a qualified professional engineer for evidence of erosion or instability. The TMA-2 cover has no visible differential settlement or indications of slope instability (e.g. tension cracks, slumping, etc.). Vegetation density is increasing with age of vegetation, suggesting that drainage conditions are supportive of self-sustaining vegetation. Some minor self-armouring erosion occurred over a few small areas during the period prior to vegetation establishment, which have been successfully prepared with placement of gravel. No other areas of erosion have been observed on completed cover to date. All drainage channels and swales have remained in good condition, with no erosion, side slope instability or damage to the erosion protection.

7 Conclusion

A ‘diffusion barrier’ type multi-layer soil cover (with a high saturation performance layer designed to limit gas migration to a diffuse flux) was designed and constructed in coordination with a long-term closure landform design to rehabilitate a TMA at a closed uranium mine. The cover comprised a 0.4 m thick compacted layer of SGB, overlain by a minimum of 1 m of sand and gravel. The landform design includes an outlet channel to remove water from the TMA and internal surface slopes of up to 10H:1V intended to provide free-draining, water-shedding conditions.

Construction of the cover and drainage system was completed in TMA-2 in 2017. Performance monitoring of the rehabilitated TMA-2 has been ongoing and supports the following conclusions:

- The SGB performance layer of the cover has maintained a high level of saturation as intended by the design at locations where topography and drainage conditions are less supportive of infiltration, on a 10H:1V slope and at near the crest of a topographic ridge.

- The cover has reduced radon flux from the tailings deposit to around 0.02 Bq/m^2/s. This value is significantly lower than the design objective of 0.3 Bq/m^2/s and represents a greater than 99% reduction from the pre-rehabilitated condition.
- The landform design and associated drainage system have been successful at maintaining physical stability of the TMA. Vegetation is becoming well established and erosion has not been observed since vegetation establishment.
- The provision of an outlet channel has eliminated the potential for overtopping of the waste rock embankment structure.
- The low hydraulic conductivity of the SGB will reduce recharge of underlying tailings, which is expected to result in reduced loading of tailings contact water to downstream environment and gradual lowering of the groundwater elevation within the tailings.

The successful performance of the cover system over closure landform slopes of up to 10H:1V has been demonstrated in this case study, providing a basis for expanding the utility of diffusion barrier covers to free-draining landforms.

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