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The Ridgeway TMF cover system after 20 years of atmospheric forcing, what we knew then and now

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Abstract

Dry cover systems are of particular interest in mitigating potential closure risks associated with tailings dam structures at closure. The Rio Tinto, Kennecott Ridgeway Mining Company (Ridgeway) tailings management facility (TMF), which was reclaimed with a dry cover system, is a unique case study spanning over twenty years of closure performance.

The lined Ridgeway TMF contains approximately 60 million tonnes of potentially acid generating tailings (PAG). Mining operations ceased in November 1999 and the TMF was reclaimed with a hydraulically placed saprolite clay water store-and-release cover system. Placement of the cover system was initiated in January 2000 and completed in May 2000. A stated key performance objective of the cover system is to maintain a high degree of saturation in the cover and tailings, thereby limiting oxygen ingress and providing geochemical stability to the potentially acid generating tailings.

Vegetation on the cover is primarily Bermuda grasses, millet, and sericea lespedeza. The vegetation was mowed (vegetation management) to maintain the grassland; however, this practice was discontinued in later years allowing for woody brush species to colonize the landform. In 2022 vegetation management was implemented to return the cover to the original grassland vegetation.

The cover system design was supported by water balance numerical simulations to evaluate performance under varying climatic conditions. In 2007 a field response numerical simulation model was developed to gain further insight into the predicted performance of the cover system. Simulated oxygen ingress was predicted to be less than ~0.2 mol/m^2/yr.

A cover system assessment program was implemented in 2022, to obtain multiple lines of evidence to support the performance of the cover system following 22-years of atmospheric forcing. The assessment program included an in-situ sampling and characterization program to assess vegetation characteristics and geotechnical and geochemical properties of the tailings and cover material. Numerical simulations were completed to evaluate climate change and mitigation measures for addressing potential performance risks.

The oxygen ingress rate through the cover system was estimated to be Low or 1 to 5 mol/m^2/yr. The simulated results suggest that vegetation management could reduce the rate of oxygen ingress. Climate change poses a potential risk to long-term performance where vegetation management may not provide adequate mitigation. The degree of saturation in the tailings and cover material in October 2022 ranged from 68% to 100%, which would support the estimated oxygen ingress. This paper presents the conceptual model of closure performance based on an information review and results of the in-situ sampling and characterization program as well as the results of the preliminary soil-plant-atmosphere numerical simulation models.

Keywords: *Tailings management facility, tailings storage facility, dry cover system, oxygen ingress, vegetation, metal leaching and acid rock drainage*

1 Introduction

The application of cover systems over potential acid generating (PAG) mine rock or tailings is a common technique for preventing and controlling metal leaching and acid rock drainage (ML/ARD) (INAP, 2017). Cover systems can be simple or complex, ranging from a single water store-and-release layer to engineered multilayered systems with capillary breaks, low permeability barrier layers, and geosynthetics. The primary objective for a cover system in managing ML/ARD is to control the ingress of water and / or oxygen to the underlying reactive mine rock or tailings.

The primary factor considered in the design and assessment of a cover system is the climatic regime in which it is situated, given that climate is a key variable driving performance. As an example, the anticipated oxygen ingress rate for a water store-and-release (WS&R) cover system located in a tropical and temperate climate would likely be less than 5 mol/m^2/yr and 100 mol/m^2/yr, respectively. Net percolation is estimated to be between 50% to 60% and 15% to 50% of rainfall, respectively (INAP 2017). Beyond the consideration of climate, a mine closure practitioner focuses on the cover system and landform design and available materials. In general, as the design criteria for water or oxygen are reduced to more stringent values, cover system complexity and cost typically increase. This inevitably results in greater considerations for physical, chemical, and biological processes that may influence the longer performance of the cover system (INAP, 2003).

The use of water covers is a common closure strategy for tailings management facilities (TMFs) that contain PAG rock; however, in an effort to reduce closure risks associated with TMFs mining companies are becoming increasingly interested in the use of dry cover systems, and where possible simple WS&R designs. This paper provides a unique case study where a WS&R cover system was used to reclaim the Kennecott Ridgeway Mining Company (Ridgeway) TMF in South Carolina. The cover system was constructed in 2000 and designed to limit oxygen ingress to the underlying PAG tailings thereby providing geochemical stability. A key aspect of the cover system is that the underlying shallow phreatic surface allows the cover system to 'punch above its weight class' under the temperate site climatic conditions and provide a Low rate of oxygen ingress (1 mol/m^2/yr to 5 mol/m^2/yr).

2 Conceptual model of closure performance

A 2023 update to the conceptual model of closure performance was developed for the TMF based on an information review, material sampling and characterization program, and water balance and oxygen ingress numerical simulations. Key information obtained from the 2022 drilling and test pitting sample and characterization programs and numerical simulations are summarized in Section 3 and Section 4, respectively to support the conceptual model herein.

The Ridgeway mine is an open pit gold mine in South Carolina that operated from 1988 to November 1999. It contains approximately 60 million tonnes of PAG tailings with an upper surface footprint of approximately 124 ha. The TMF is lined with a composite barrier layer consisting of a HDPE geomembrane and compacted clay layer; hence any leakage from the facility to the shallow groundwater is expected to be low, of which is supported through a water balance analysis.

In 1997 the tailings deposition process was used to create the reclamation landform by using a central and perimeter deposition. In the spring of 1998, the pond in the TMF increased to greater than 60% of the surface area and then in the autumn it increased further to ~88% in response to hurricane Bonnie and Earl resulting in the majority of tailings deposition occurring sub-aqueous (SRK, 2000).

The TMF was reclaimed with a hydraulically placed saprolite clay WS&R cover system with a targeted thickness of 0.9 m (3 ft). Survey results provided an as-constructed cover thickness of >1.2m (4ft) for 60% of the surface area and between 0.9 m (3 ft) and 1.2 m (4 ft) for 33% of the area. The remaining 7% of the surface area was estimated to be less than 0.9 m (3 ft) (Duckett and O'Kane, 2006). The objective of the cover system is to provide non-contact discharge water from the TMF and maintain geochemical stability through controls on oxygen ingress. Predicted performance of the final cover system indicated that under dry extreme climatic conditions, a minimum degree of saturation of 85% would be maintained in the cover material and tailings (SRK, 2000).

Hydraulic placement of the cover system was initiated in January 2000 and completed in May 2000 (Duckett et. al., 2012). A central and perimeter deposition process was used for the tailings and cover to create a horseshoe shaped topography with slopes of 0.5% to 1% which directs surface water from the southwest of the TMF to a spillway at the northeast corner as shown in Figure 1. The cover material was deposited in a series of layers with the deposition point moved to achieve the required thickness and final landform. This resulted in random layers of saprolite that had different geological properties and varying depth spatially across the landform. The soil pH during placement was moderated with the lime plant to be between 7.5 and 8.5 (SRK, 2000). It is likely that the large pond area, sub-aqueous deposition, and relatively short pause between tailings and cover material deposition (about 1 month) would have limited the exposure of sulfides within the tailings to oxidative conditions and optimized the retention of the initial finite amount of alkalinity in the tailings during the final years of deposition.

Figure 1 The Ridgeway TMF illustrating the surface water management and discharge to the spillway at northeast location (after Duckett et. al,. 2012)

Material in the saprolite borrow area consisted of weathered red, brown, and purple saprolite and a grey and green saprolite from greater depth. The excavated material was fed into the mill where it was ground and transported as a slurry on the surface of the TMF. The cover borrow material is fine textured and with a typical fines content (<0.076 mm grain size) of greater than ~65%. The hydraulically placed cover system developed desiccation cracks in 2001 that extended nearly the full depth of the cover profile. The density of the cover system increased with improved trafficability, and by 2004 the cracks eventually infilled with sediment (Duckett and O'Kane, 2006).

In 1999 two tailings samples were analyzed by acid base accounting (ABA) techniques and thought to reflect tailings deposed in the last year of deposition. It was noted that the samples represented a blend of the low-grade ore stockpile and North Pit ore. The samples provided a sulfide content of approximately 1% and neutralizing potential (NP) of 62 t $CaCO_3$/kt (SRK, 2000), providing a neutralization potential ratio (NPR) of 2.5. Samples of tailings collected in 2005 (Duckett et. al., 2012) and 2022 (Rio Tinto, 2023) provided a neutralizing potential in the range of approximately 10 t $CaCO_3$/kt to 14 t $CaCO_3$/kt; however, this was reduced to less than 9 t $CaCO_3$/kt in the shallower depth of the tailings profile. Detailed sampling of tailings immediately below the cover system / tailings interface demonstrated, by ABA that NP ranged from 2 t $CaCO_3$/kt and 7 t $CaCO_3$/kt and an NPR of less than 0.19 (WSP, 2023). The neutralizing potential at a depth of 0.6 m below the cover / tailings interface ranged from 4 to 10 t $CaCO_3$/kt. The NPR of the tailings tends to be less than ~0.5 within the top six meters of the tailings profile. While there is some uncertainty related to the geochemical characteristics of tailings placed near the end of mine life, the information review and field sampling would suggest that the NP was likely in the range of 10 to 14 t $CaCO_3$/kt. If an initial NP of 62 t $CaCO_3$/kt was considered it is anticipated that the sulfide content would be lower than current observed values.

The pH in the tailings mass is relatively consistent and ranges from 7.8 to 8.2 through the tailings profile; however, at the cover system / tailings interface the tailings pH ranges from 3.6 to 7.6. The observed low neutralizing potential and associated acidic conditions would suggest that there is some variability in the rate of sulfide oxidation spatially across the cover system following twenty-two years of atmospheric forcing. Duckett et. al., (2012) indicated that tailings pH remained at approximately 8.3 in 2005 and there was no evidence of sulfide oxidation. This would further support the conceptual model of a gradual reduction in NP over the 22-year cover system service period.

The depletion in NP and a measurement of stored acidity was used as a surrogate to estimate oxygen ingress through the cover profile. The 2023 conceptual model of closure performance considered the following oxygen ingress classifications:

- Very Low: < 1 mol/m^2/yr;
- Low: 1 mol/m^2/yr to 5 mol/m^2/yr;
- Moderate: 5 mol/m^2/yr to 10 mol/m^2/yr;
- High: 10 mol/m^2/yr to 50 mol/m^2/yr; and
- Very High: >50 mol/m^2/yr.

Based on ABA data it is anticipated that areas of the cover system would be classified as having Very Low and Low rates of oxygen ingress. Assuming that any loss of NP is attributed to tailings sulfide oxidation, the overall oxygen ingress rate for the TMF cover system would be classified as Low.

The degree of saturation obtained from undisturbed tailings and cover material samples in 2022 ranged from 68% to 100% and would support the likely range of oxygen ingress given the October 2022 sampling period. In 2001, the field oxygen concentrations measured above the tailings interface ranged from 3.1% to 14.1%. The measured oxygen concentration in the tailings below a thinner 0.8 m (2.6 ft) cover profile was 2.8% and for areas with a thicker 1.2 m (4 ft) profile 0.3% was reported (O'Kane, 2002). It was also noted that additional work was required to vet the monitored pore-oxygen concentrations. Previous numerical simulations of cover system performance provided estimated average oxygen ingress rates of 0.1 mol/m^2/yr for a 1.2 m (4 ft) cover profile and 0.2 mol/m^2/yr for a thinner 0.8 m (2.6 ft) cover profile (O'Kane, 2007), an order of magnitude lower than current conceptual model estimates.

The climate at Ridgeway is classified as *Cfa* (*C*-Temperate, *f*-without dry season, *a*-hot summer) based on the Koppen-Geiger climate classification. Oxygen ingress rates for a typical water store-and-release cover system under Ridgeway site climatic conditions would likely be classified as Very High and > 50 mol/m^2/yr (INAP, 2017). However, in the instance of the Ridgeway cover system the shallow phreatic surface in the TMF attenuates the development of high negative pore-water pressures, that serve to desaturate the cover and tailings, when the atmospheric demand for water is high. In general, the phreatic surface is near or within the cover profile for two to six months per year and then in the spring and summer decreases to an average of approximately 1.8 m to 2.4 m (6 to 8 ft) below the interface.

The NP of the cover material in generally between 1 t $CaCO_3$ / kt and 4 t $CaCO_3$ /kt (based on 2022 test pitting) with NPR values between ~0.1 and ~13.0, highlighting PAG and non-acid generating (NAG) cover material.

Field paste pH of the cover material at four of the six test pit locations was less than 5 and as low as 3.1. Sulfate concentrations in runoff from the TMF were noted to range from approximately 100 mg/L to 600 mg/L (Duckett et. al., 2012) and likely due to oxidation of sulfides in the cover material. It is noted that the depletion of neutralization capacity in the tailings could be in part due to acidity generated in the cover profile and flushing down into the tailings. Hence, additional analysis is required to refine the geochemical conceptual model to account for the potential downward loss or flushing of alkalinity and observed acidity generated in the cover profile.

Based on an analysis of ABA data (paste pH and NAG pH) the 2023 conceptual model considered the following ML/ARD risk classifications:

- NAG;
- Uncertain;
- PAG Low Risk, lag time to ARD onset;
- PAG Medium Risk, rapid ARD; and
- PAG High Risk, immediate ARD.

Based on the ABA data the tailings are either classified as PAG Low Risk or PAG High Risk. Cover material samples were classified as PAG High Risk, Uncertain, and NAG.

Vegetation on the cover is primarily Bermuda grasses (*Cynodon dactylon*), millet (*Urochloa ramosa*), and sericea lespedeza (*Lespedesa cuneata*). Vegetation was managed / mowed to maintain a grassland; however, this practice was discontinued in later years allowing for woody brush species to colonize the landform such as groundsel bush (*Baccharis halimifolia*). Between 2020 and 2022 the vegetation was mowed to return the cover to the original grassland vegetation. Preliminary numerical simulations suggest that vegetation management may mitigate performance risks associated with the cover system, reducing the overall cover system oxygen ingress to Very Low. Vegetation management attenuates water losses through plant transpiration from the TMF. In the 2022 test pitting program, roots were observed extending down desiccation crack into the tailings and promoting sulfide oxidation; however, this did not appear to be widespread and was possibly restricted to areas of thinner cover profile.

Numerical simulations completed herein suggest that climate change, assuming RCP8.5 (highest baseline emissions in which emissions continue to rise through the twenty-first century (U.S. Geological Survey, 2015)), could result in approximately one order of magnitude increase in the oxygen ingress, providing a High oxygen ingress classification (i.e., >10 mol/m^2/yr) for the TMF. Irrigation of water on the surface of the TMF is a viable option for mitigating cover performance risks and would likely require 50 to 100 mm/month (~75,000 to 125,000 m^3/month) over June, July, and August.

The numerical simulations completed in this assessment are based on a generalized field response model and it is anticipated that a discretized model is required to simulate the layered structure of the hydraulically placed tailings and cover material more accurately.

3 Field monitoring, sampling, and characterization program

This section provides a summary of key test results obtained from field sampling and characterization programs and site monitoring data used to support the conceptual model of closure performance.

3.1 Degree of saturation

In 2022 undisturbed tailing and cover material samples were collected from six test pits using a steel cutter sampling ring, with samples primarily collected immediately above and below the cover system / tailings interface. The samples of known volume were submitted for oven dry water content (ASTM D2216), specific gravity (ASTM D854), and particle size analysis (ASTM D422). Using the volume of the voids, solids, and water, the degree of saturation was calculated for each sample. The results of the degree of saturation analysis are shown Figure 2. It is noted that the reported values exceed 100% with a maximum of 104%. When considering the results this may suggest that the error associated in the analysis is in the range of +/- 4% of the reported value.

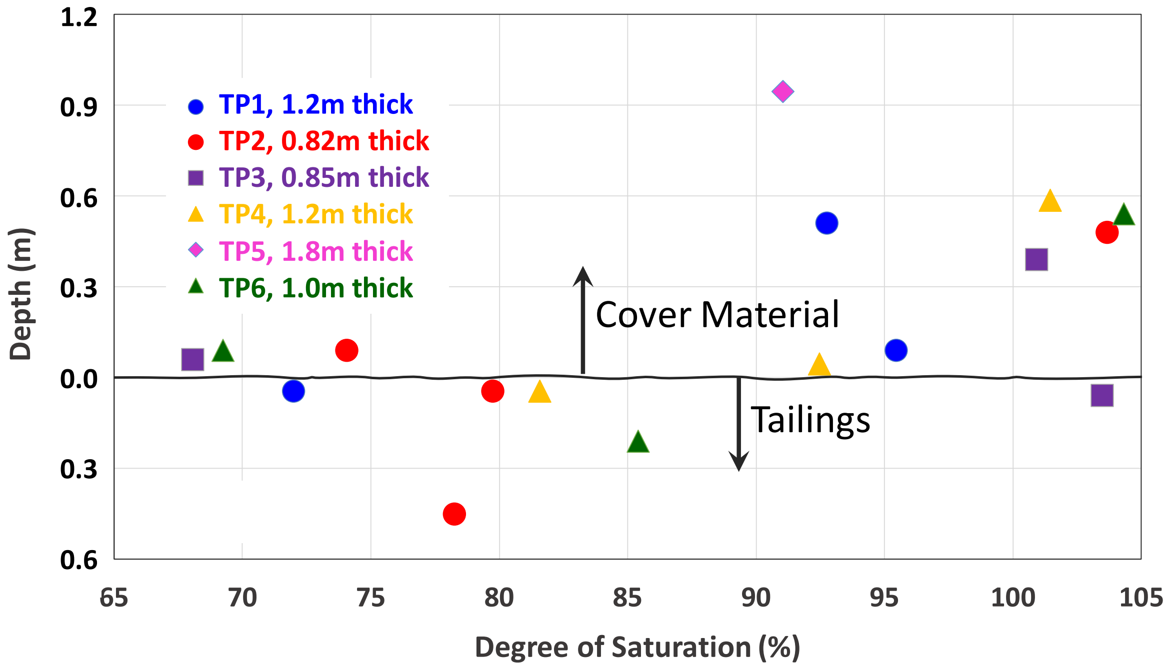

Figure 2 Degree of saturation measured in the cover system and tailings

The degree of saturation in the tailings and cover material sampled on October 27th, 2022 ranged from 72% to 103% and 68% to 104%, respectively (see Figure 2). The observed degree of saturation is a key performance metric and indicates that the oxygen diffusion coefficient may not be suppressed to the extent possible at all test pit sampling locations. The lowest degree of saturation was observed at Test Pit 1, Test Pit 2, Test Pit 3, and Test Pit 6. Sample collection at Test Pit 5 was limited to a shallow depth of excavation due to pore-water being expressed at the base of the test pit. Acidic conditions in the tailings were observed at Test Pit 2 and Test Pit 3 with a pH of 3.6 and 3.8, respectively. This would suggest that the oxygen ingress rate was high enough to generate sufficient acidity to consume the NP and provide acidic conditions. Understanding that Duckett et. al., (2012) reported that all tailings samples in 2005 were alkaline and did not exhibit any signs of oxidation would suggest a progressive depletion of NP over the 22-year cover system service period.

When considering the degree of saturation results presented in Figure 2, it should be noted that the degree of saturation varies with depth due to distance from the surface, atmospheric forcing (i.e., rainfall and evapotranspiration), and influence of the layered profile created by the hydraulic placement of the materials. For example, at Test Pit 3 the degree of saturation in the cover was ~100% at 0.4 m (1.2 ft) above the cover system / tailings interface and then decreased to ~68% immediately above the interface. In the tailings just below the interface the degree of saturation then increased to ~100%. This means that while there may be locations where the degree of saturation decreases below the 85% criteria for oxygen diffusion, there may be discrete layers in the profile that maintain a degree of saturation greater than 85%. Subsequently the layering or textural contrast through the profile may provide for slight breaks in the pressure profile, enhancing the water retention of discrete layers.

Diffusion of oxygen across the cover system was estimated based on the coefficient of oxygen diffusion (De) after Aachib et. al., (2004) and the use of Fick's Law. Estimates of oxygen diffusion were calculated for a range of degree of saturations across a 0.5 m thickness of the cover profile and are summarized in Table 1. The diffusive oxygen to the tailings was estimated for 182 day period (estimated period with lower phreatic surface elevation). The estimated oxygen ingress rates based on the degree of saturation appear reasonable to support the estimates developed from the ABA data in the following section.

Table 1 Calculated oxygen ingress for a range of degree of saturations

Degree of Saturation (%)	Oxygen Diffusion ($g/m^2/yr$)	Oxygen Diffusion ($mol/m^2/yr$)
80	279.4	8.7
85	108.3	3.4
90	28.6	0.9
95	2.7	0.1

3.2 Acid base accounting

This section presents key information to support the conceptual model for closure performance related to oxygen ingress. ABA data were used to estimate the oxygen ingress into the tailings. ABA data summarized in Rio Tinto (2023) and WSP (2023) were compiled to inform on the pH and NP in the tailings mass. The pH and NP (as t $CaCO_3$/kt) for the tailings are shown in Figure 3 and Figure 4, respectively. pH across the tailings profile is consistent at approximately 7.8; however, just below the cover interface pH ranges from 3.6 to 7.7. The NP within the tailings profile is generally in the range of 10 t $CaCO_3$/kt to 14 t $CaCO_3$/kt; however, it is observed to decrease within the near surface tailings to values of 2 to 10 t $CaCO_3$/kt.

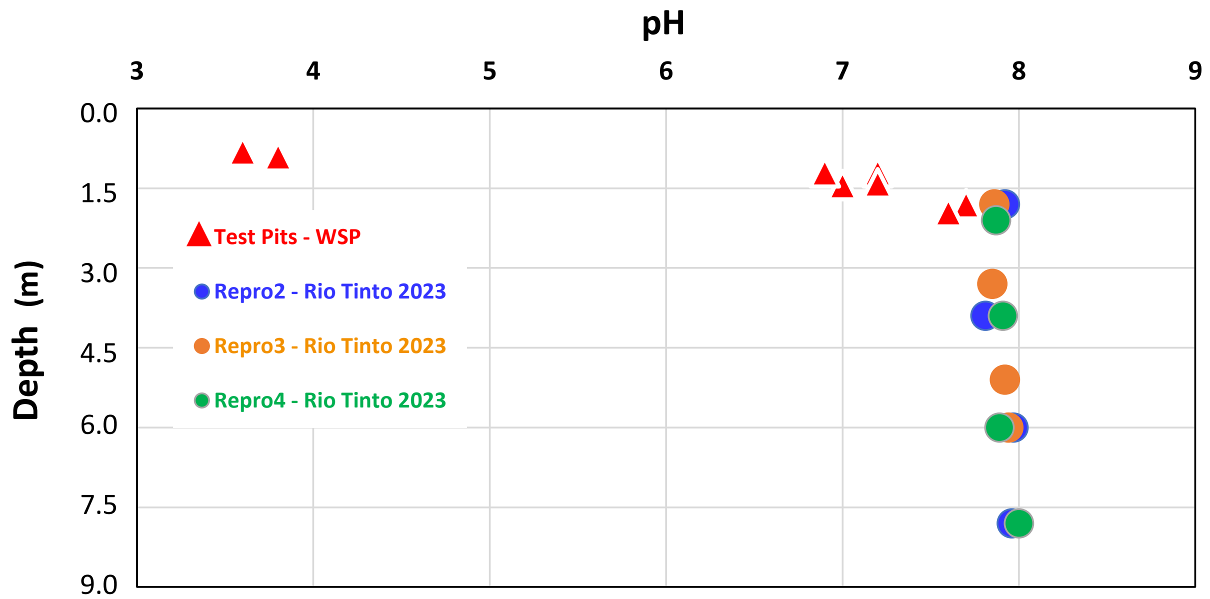

Figure 3 pH as a function of depth in the tailings based on test pitting and drilling programs conducted in 2022 (pH of pore-water)

ABA data was used to classify the ARD risk of the tailings and cover materials sampled in the 2022 test pit program with the results summarized in Figure 5. The tailings are classified as either PAG High Risk or PAG Low Risk. The PAG Low Risk reflects tailings with existing NP, while the PAG High Risk indicates an existing load of stored acidity. The PAG Low Risk tailings provide an opportunity to extend the lag time to acid onset through controls on oxygen ingress. The cover material provides a grouping of samples that fall within the zones of PAG High Risk and Uncertain classification with an additional grouping of NAG samples. Mitigation strategies to manage the PAG High Risk and Uncertain cover material will include the application of lime to the cover. Additional characterization and interpretation of the cover material ABA data will be required to assess potential ML/ARD closure risk.

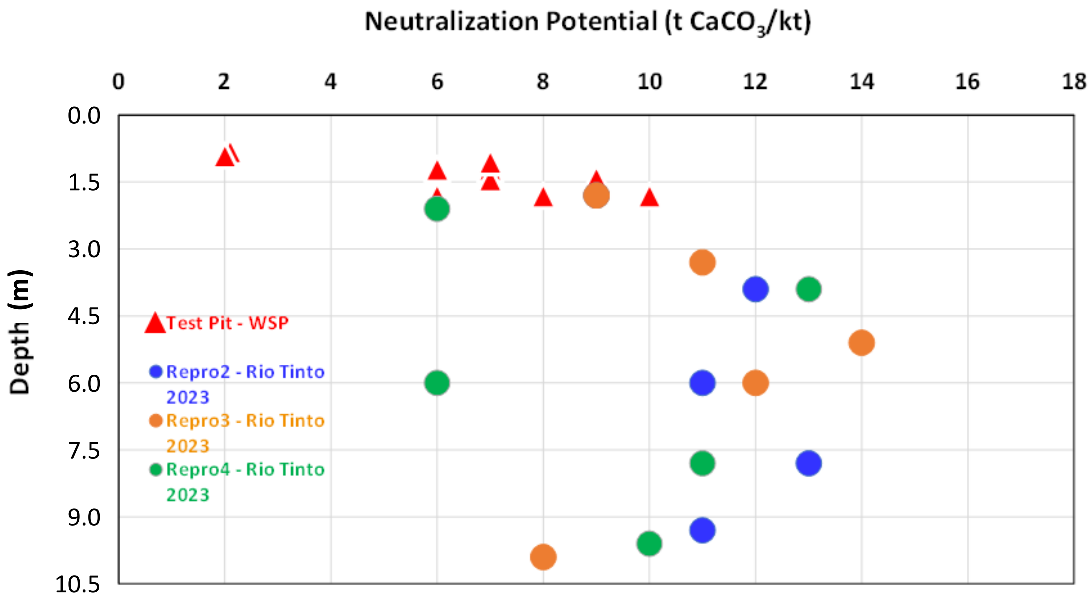

Figure 4 NP as a function of depth in the tailings based on test pitting and drilling programs in 2022

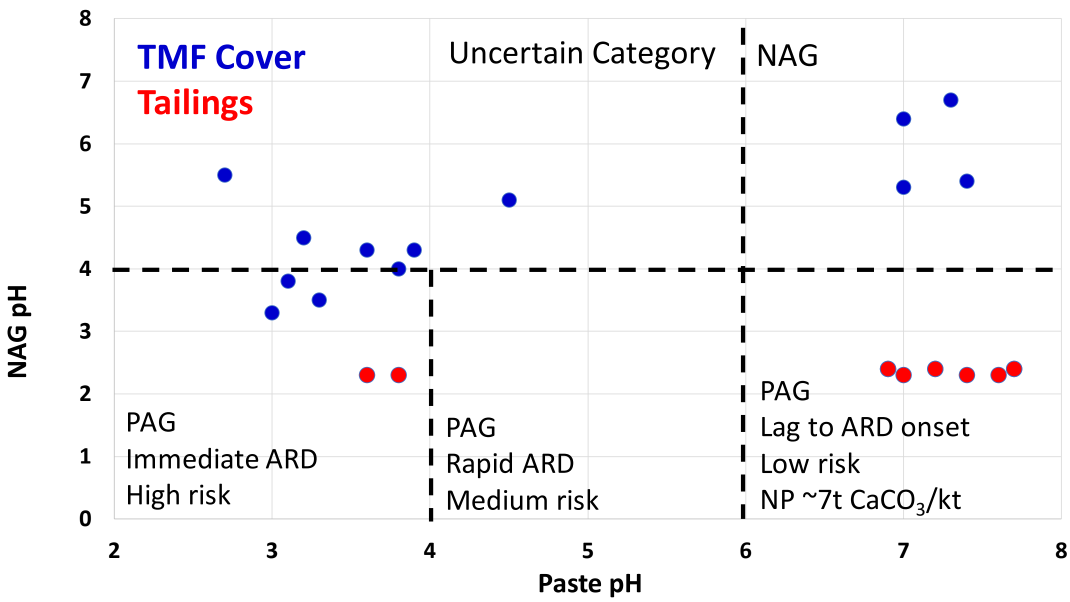

Figure 5 Paste pH and NAG pH ARD risk classification of tailings and cover material from test pit samples

The conceptual model of closure performance assumes that the NP within the tailings was maintained until after the cover system was fully constructed due to the short pause between tailings and cover material hydraulic placement, the large pond area during deposition, and primarily subaqueous tailings deposition in the final year of deposition. This is further supported by non-acidic tailings as previously reported in 2005 (Duckett et. al., 2012) suggesting that acidic tailings were not evident at an as-constructed condition.

Subsequently, it is assumed that any observed depletion of alkalinity is the result of buffering of acidity generated over the 22-year cover system service period due to oxygen ingress (and sulfide mineral oxidation).

The analysis for estimating oxygen ingress assumed that:

- The reduction in NP occurred within the tailings to a depth of 0.3 m below the cover system tailings interface, which is supported by the field sampling (test pits and drilling);
- Oxygen ingress to the tailings has occurred over a 22-year period;
- A tailings dry density of 1.54 Mg/m^3 is used to convert mass to cubic meters;
- Assumed that 2 moles of H+ will be produced per mole of sulfur; and
- Assumed that 1 mole of $CaCO_3$ neutralizes 2 moles of H+.

The analysis assumes two bookend scenarios:

- Very Low oxygen ingress – NP is largely retained and decreases from an average background of 12 t $CaCO_3$/kt to 10 t $CaCO_3$/kt; and
- Low oxygen ingress – NP decreases from an average background of 12 t $CaCO_3$/kt to 2 t $CaCO_3$/kt.

Stored acidity in the tailings was also included in the analysis, with the results summarized in Table 2. The estimated oxygen ingress to support the reduction in NP for areas with bookend Very Low and Low ingress could be in the range of 0.78 $mol/m^2/yr$, and 3.9 $mol/m^2/yr$, respectively.

Table 2 Estimated oxygen ingress based on depleted NP and stored acidity

Scenario	Consumed NP (t $CaCO_3$/kt)	Consumed NP (kg $CaCO_3/m^2$)	Acidity mol (H_2SO_4/m^2)	Oxygen Flux (mol/m^2)	Oxygen Flux ($mol/m^2/yr$)
		Neutralizing Potential Depleted			
Very Low	2	0.92*	9.2	17.2	0.78
Low	10	4.62*	46.3	86.6	3.9
		Stored Acidity			
Very Low	0.03	0.005**	0.05	0.09	0.004
Low	2.88	0.45**	4.5	8.41	0.38
				Total for Very Low	**0.78**
				Total for Low	**4.28**

*calculated over a 0.3m depth based on field data and sampling interval.
**calculated over a 0.1m depth based on field data and sampling interval.

The calculated acidity for neutral and acid tailings was estimated at 0.03 t $CaCO_3$/kt and 2.88 t $CaCO_3$/kt, respectively. With the stored load of acidity applied over a depth of 0.1 m, estimated annual oxygen ingress rate to support the stored load over the cover system service period would be 0.004 $mol/m^2/yr$ to 0.38 $mol/m^2/yr$. The stored acidity load was calculated using an ion balance; however, given that acidic tailings were observed with a pH in the range of 3.5 there could be an unaccounted stored load associated with melanterite-type acidity / jarosite-type acidity. The stored acidity load associated with melanterite could account for up to possibly 10 t/kt of acidity as $CaCO_3$. Additional testing will assist in assess this potential stored load. Depending on the ABA data there is the potential that the Low oxygen ingress classification could increase to a Moderate classification.

The analysis, based on depleted NP and stored acidity load, suggests that potential bookend oxygen ingress rates for the cover system might be 0.78 $mol/m^2/yr$ for the Very Low and <4.28 $mol/m^2/yr$ for the Low. It is noted that the estimated rates of oxygen ingress are lower than that reported for a typical WS&R cover system (10 to 100 $mol/m^2/yr$) under similar site climatic conditions (INAP, 2017) to that of Ridgeway, and highlights the importance of the shallow phreatic surface in optimizing cover system performance.

The conceptual model of closure performance based on ABA data will be further advanced to account for melanterite-type acidity / jarosite-type acidity, depletion of NP possibly attributed to potential acidity generated in the cover profile, the potential loss of alkalinity with infiltrating water, and oxygen consumed in the cover profile.

4 Forecasting cover system performance

Generalized field response models were developed to simulate cover system performance guided by the conceptual model of closure performance. Development of the field response models included simulation of the phreatic surface and the degree of saturation measured in the cover and tailings in 2022. The field response model was then used to simulate oxygen ingress and then compared to the estimated oxygen ingress established within the conceptual model of closure performance.

The SoilVision software version 10.02.00.293 (Bentley, 2020) was used in the numerical simulation program. Historic climate data over the cover system service period (2000 to 2020) was used as the upper boundary conditions to simulate water balance parameters, while a shortened database from 2006 to 2011 was used to simulate oxygen ingress given the longer timeframe to complete the coupled simulations. Annual rainfall over the 20-year cover system period is shown in Figure 6. Average rainfall and potential evaporation over the 20-year period was 1,149 mm/yr and 1,250 mm/yr, respectively.

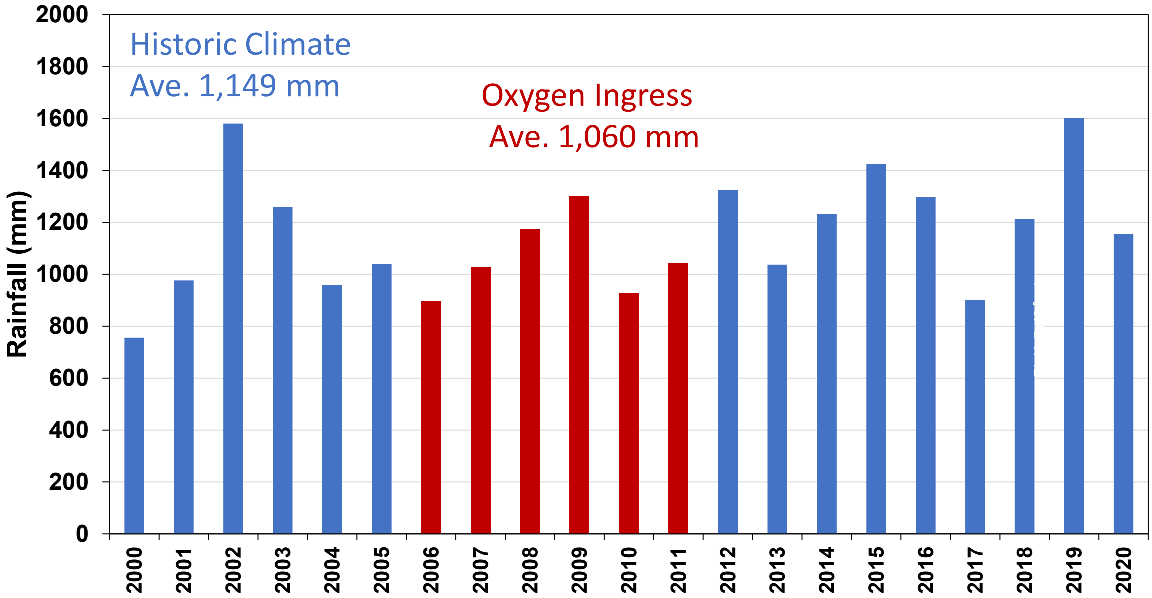

Figure 6 Annual rainfall over the 2000 to 2020 period

Root characteristics were estimated based on the 2022 test pitting program. Vegetation to reflect managed and unmanaged vegetation was also evaluated. Unmanaged vegetation is considered to include Bermuda grasses, millet, sericea lespedeza, and woody shrubs such as groundsel bush but does not include trees. Hence, the unmanaged scenario would still require mowing of the cover system potentially every 10 years to keep trees from colonizing the landform. An unmanaged vegetation cover increases the store and release of water through higher rates of transpiration. This reduces the degree of saturation and subsequently increases diffusive oxygen ingress. Managed vegetation in the model directs a greater proportion of the atmospheric energy to surface evaporation as opposed to transpiration.

The lower boundary condition was simulated as a zero-flux boundary at the base of the tailings profile to simulate the composite liner system.

4.1 Simulated oxygen ingress

The field response numerical models were established to demonstrate that the model can reasonably simulate field conditions. A stepwise approach was utilized for the TMF and is as follows:

1. Establish two soil-plant-atmosphere (SPA) simulation models that reasonably replicate bookend changes in the phreatic surface and in-situ measured degree of saturation over the 2022 period. The 2022 period was selected given the automated measurement of the phreatic surface and test pit results;
2. Utilize the two SPA models to simulate oxygen ingress to validate the model and inform on potential oxygen ingress over the service period of the cover system. A six-year period of 2006 to 2011 was used in the assessment; and
3. Utilize the two SPA models to simulate the degree of saturation in the cover and tailings profile over the cover system service period of 2000 to 2022 to inform on potential mitigations measures.

Calibration to the phreatic surface provided the development of a Finer Scenario (with a higher air entry value for the cover material) and Coarser Scenario (with a lower air entry value for the cover material). Results of the calibration to the phreatic surface are summarized in a probability of exceedance data analysis as shown in Figure 7 and compared to the average and bookend measured phreatic surface (i.e., CPT-9 and CPT-11) in the TMF. At depths greater than 3.0 m (10 ft) the Coarser Scenario correlated better to changes in the phreatic surface than was observed for the Finer Scenario. While the monitored phreatic surface provided a metric for calibration of the field response model, it should be noted that a SPA model that can accurately replicate a cover system water balance may exhibit greater difference in simulating a shallow phreatic surface in finer textured materials due to the high air entry value of the material.

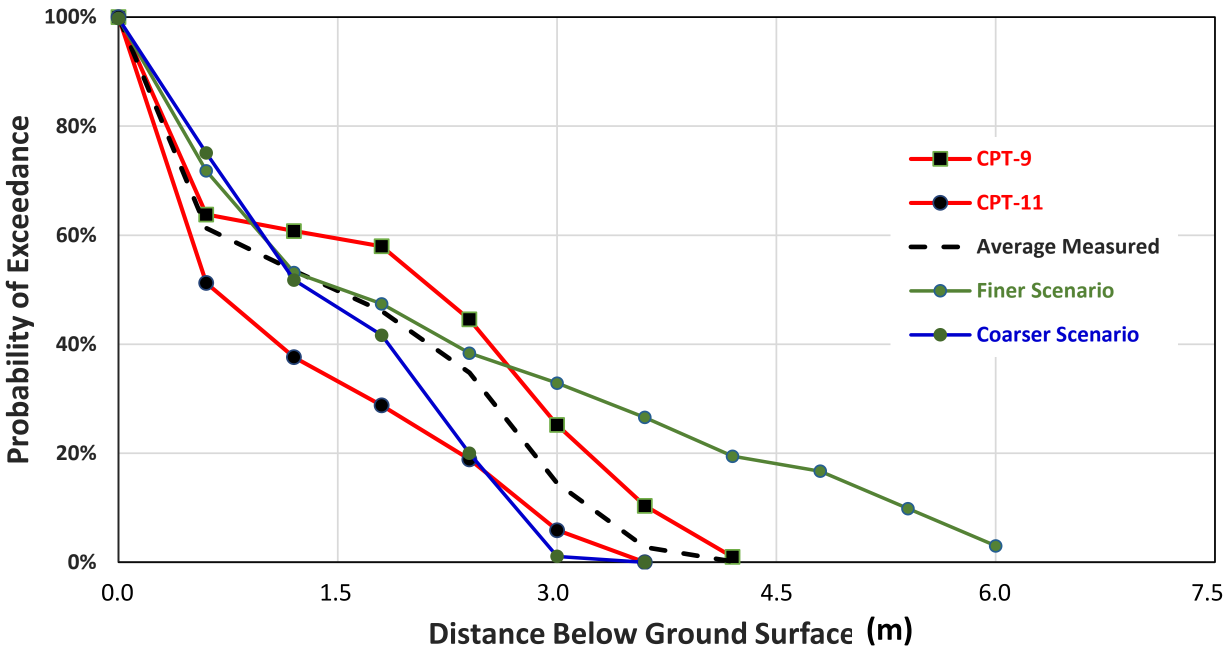

Figure 7 Probability of exceedance of the measured phreatic surface in 2022 at the CPT-9 and CPT-11 stations compared to that simulated for the Finer Scenario and Coarser Scenario

The oxygen ingress simulations for the Finer Scenario and Coarser Scenario provided mean oxygen ingress rates of 2.1 mol/m^2/yr and 123 mol/m^2/yr as shown in Figure 8. The Finer Scenario was adopted as the Low oxygen ingress scenario, while the Coarser Scenario was not assessed further given the Very High rating.

The results of the phreatic surface and oxygen ingress simulations suggest that a discretized field response model may be required to reflect anticipated layering in the cover and tailings due to the hydraulic placement method. Nevertheless, the Finer Scenario was advanced in the numerical simulation program to provide an understanding of potential performance risks for a cover system with a Low rate of oxygen ingress. When assessing the Finer Scenario under the RCP8.5 climate change scenario the oxygen ingress classification increased from Low to High as illustrated in Figure 8. The climate change database was developed using the National Climate Change Viewer (NCCV) (U.S. Geological Survey, 2015). The General Circulation Model (GCM) used in the analysis was considered conservative given that it provided the greatest reduction in rainfall compared to the majority of other GCMs by the NCCV. When interpreting the climate change simulation, a key aspect to consider is that the objective was not to predict performance but to identify potential long-term performance risks.

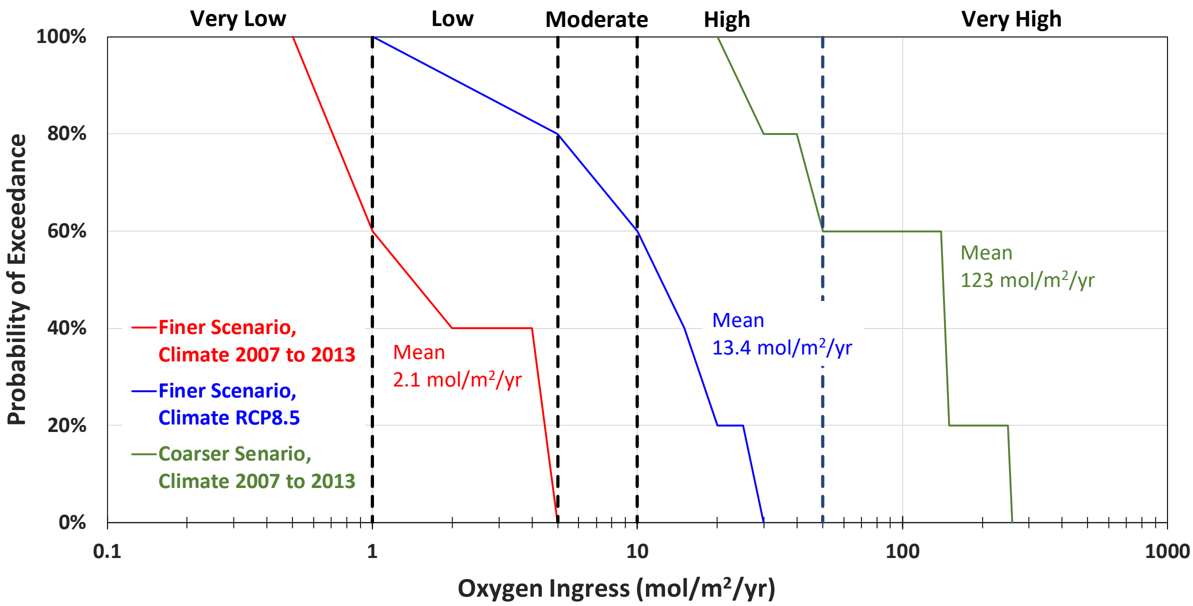

Figure 8 **Simulated oxygen ingress for the Finer Scenario and Coarser Scenario. Finer Scenario using climate change RCP8.5. Oxygen ingress classification ranges for oxygen after INAP 2017**

4.2 Simulated degree of saturation

Twenty-year numerical simulations using historic climate data (2000 to 2020) and climate change RCP8.5 (2179 to 2199) were completed to simulate the degree of saturation in the lower cover profile to evaluate performance in a comparative analysis. Alternate scenarios were simulated to assess the effectiveness of mitigation measures in addressing performance risks. The degree of saturation results summarized in a probability of exceedance analysis are summarized in Figure 9. The Finer Scenario and Coarser Scenario provided a 50% probability of exceeding 0 and 300 day per year where the degree of saturation is less than 85%. As previously noted, the Coarser Scenario was discontinued give the Very High oxygen ingress classification.

Vegetation management for the Finer Scenario reduced the 20% probability of exceeding ~160 day per year to 50 days per year. This would suggest that through a vegetation management plan the number of days where the degree of saturation is below 85% can be attenuated for areas of the cover system with a Low oxygen ingress rating. Vegetation management would require that a leaf area index of less than 0.8 is maintained throughout the entire growing season.

The Finer Scenario simulated with climate change provided an increase of 0 to 120 day at the 50% exceedance. As a mitigation measure for climate change irrigation was applied two times per month for a total of 50 mm/month in June, July, and August. Irrigation suppressed the increased atmospheric demand for water under climate change, likely reducing the oxygen ingress to rates lower than current conditions. Increasing irrigation to 100 mm/month over the three-month period substantially reduced the probability of the cover desaturation and would likely provide a Very Low oxygen ingress for the entire landform.

Without vegetation management it is anticipated that the existing NP would be depleted in approximately 20 years; however, with vegetation management and assuming a Very Low rate of oxygen ingress is reached the NP could possibly be extended over 100 years.

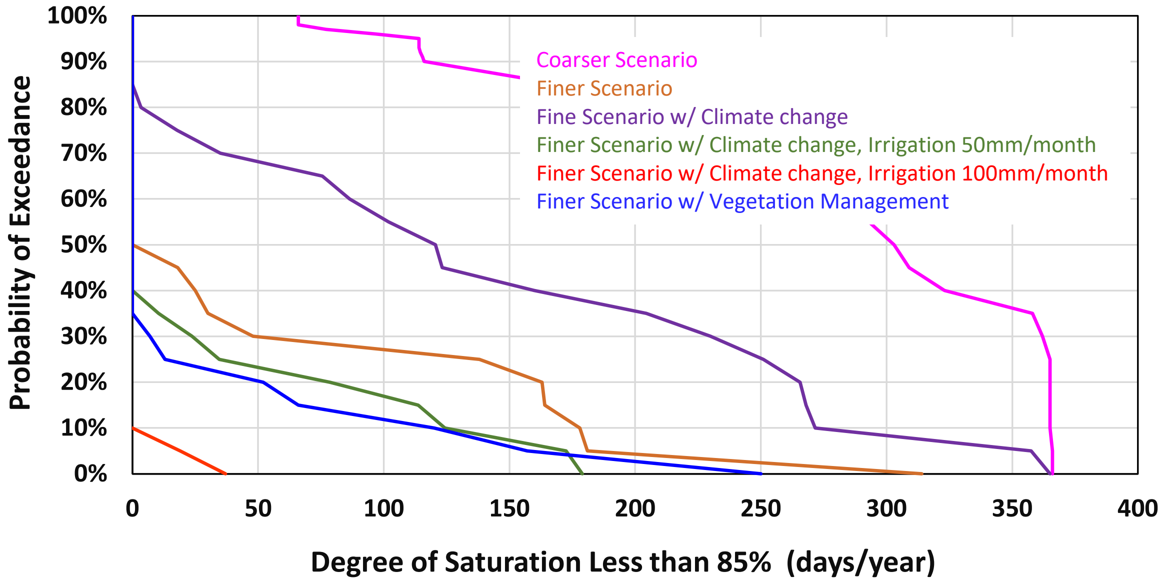

Figure 9 Simulated degree of saturation in the low portion of the cover system

5 Conclusion

Following twenty-two years of atmospheric forcing the Ridgeway TMF WS&R cover system is performing well and providing geochemical stability to the tailings. It is anticipated that the cover system has a Low (1 mol/m^2/yr to 5 mol/m^2/yr) oxygen ingress classification, while there are likely areas of the cover system where the oxygen ingress rate is Very Low (<1 mol/m^2/yr). The estimated oxygen ingress rate established within the conceptual model of closure performance is approximately one order of magnitude greater than that predicted with previously completed numerical simulations and highlights the importance of coupling numerical simulation programs with an established conceptual model supported by direct field testing and a characterization program.

The implementation of a vegetation management plan appears to show benefit in possibly reducing the Low oxygen ingress rate to that of Very Low. Without vegetation management it is anticipated that the existing NP would be depleted in approximately 20 years; however, with vegetation management it could possibly be extended over 100 years. Climate change may pose a risk to long-term performance and possibly result in an increase in the oxygen ingress from a Low to a High (>10 mol/m^2/yr) rating. Climate change (using RCP8.5) risk could likely be mitigated through a combination of vegetation management and irrigation.

Following the current assessment there is still some uncertainty as to the key factors contributing to differences in observed performance (i.e., areas with Very Low and Low oxygen ingress), such as cover / tailings texture, layering (reflective of hydraulic placement), cover thickness, location on the landform, and vegetation characteristics. Further refinement of the conceptual model of closure performance to enhance this understanding will enable potential mitigation measures to be assessed and implemented with greater confidence. Additional data analysis, characterization, and / or field monitoring may be required to advance the conceptual model, assess mitigation measures, and further refine the method of estimating performance of the cover system from a landform perspective.

The Ridgeway case study highlights the use of simple hydraulically placed WS&R cover system in providing geochemical stability to PAG tailings under climatic regions where there is a high atmospheric demand for water. The shallow phreatic surface plays a key role in the observed performance and allows the WS&R cover system to attain such high controls on oxygen ingress. This case study highlights an opportunity of achieving geochemical stability without the use of a highly engineered cover system or water cover and thereby reducing closure risks.

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