ATTACHMENT C

INTERA Memorandum Re: Pit 1 Backfill at St. Anthony Mine, Groundwater Rebound in the Jackpile Sandstone and Flow into the Dakota Sandstone (INTERA, 2021)

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TECHNICAL MEMORANDUM

To: **United Nuclear Corporation (UNC)**

From: **INTERA Incorporated (INTERA)**

Date: **5 November 2021**

Re: **Pit 1 Backfill at St. Anthony Mine, Groundwater Rebound in the Jackpile Sandstone and Flow into the Dakota Sandstone**

This memorandum presents INTERA's evaluation of the hydrogeological consequences of different backfill alternatives for Pit 1 at the St. Anthony Mine site ("Site"). If the backfill top elevation in Pit 1 maintains the evaporative hydraulic sink presently operating in the pit, poor-quality groundwater within Pit 1 will remain there.[1] Maintaining the evaporative sink in Pit 1 requires that the top elevation of the backfill remain lower than the lowest elevation of the contact between the Jackpile and the Dakota Sandstones ("Contact Surface") within the pit. Alternatively, if the backfill top elevation extends above the lowest Contact Surface elevation in the pit, Pit 1 will no longer behave as a hydraulic sink, causing Jackpile Sandstone ("Jackpile") groundwater heads to rise and allowing poor-quality groundwater in Pit 1 to migrate out from the pit into the Jackpile Sandstone and overlying Dakota Sandstone ("Dakota").

To evaluate the environmental consequences for differing backfill levels in St. Anthony Pit 1, INTERA addressed the following two questions:

1) Will backfilling Pit 1 to a level above the lowest elevation on the Contact Surface create a pathway for poor-quality groundwater in Pit 1 and the surrounding Jackpile to flow into the overlying, and presently unsaturated, Dakota?
2) Will the flow of Jackpile groundwater into the unsaturated Dakota in and around Pit 1 reach downgradient areas where the Dakota is saturated?

Based on the evidence and analyses described below, the answer to both questions is "Yes." This memorandum explains the hydrogeologic conditions that will cause flow of poor-quality groundwater from Pit 1 into the presently unsaturated Dakota formation and its eventual migration into areas where groundwater is present in the Dakota. The memorandum also summarizes site conditions and previous modeling studies.

Site Conditions

As is described in the St. Anthony Stage 2 report (INTERA, 2015), the Jackpile and the overlying Dakota are exposed within Pit 1, but only the Jackpile contains groundwater near the pit. On a regional scale, groundwater in the Jackpile flows from the north and northwest, where groundwater heads are highest, toward the south and southeast, where groundwater heads are lowest (**Figure 1**). Evaporation of the

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[1] The poor-quality groundwater in Pit 1 refers to the poor-quality groundwater flowing into Pit 1 from the Jackpile Sandstone and the current expression of water in the bottom of Pit 1.

expressed water present in Pit 1 acts like a well pumping from the Jackpile and continues to decrease groundwater heads around the pit, creating a groundwater cone of depression (INTERA, 2006, 2015, 2017, 2019; see **Figure 1** groundwater head contours in and around Pit 1). Jackpile groundwater flows into Pit 1 because evaporation removes inflowing groundwater at a rate sufficient to keep the elevation of the expressed water very close to the pit floor's lowest elevation of about 5,850 feet above mean sea level (ft amsl). This elevation is the lowest observed Jackpile groundwater head (**Figure 1**). Eliminating the evaporation-driven removal of Pit 1 expressed water is expected to cause Jackpile groundwater heads in and around the pit to increase (INTERA, 2006, 2015, 2017, 2019, and following section).

The Contact Surface defines the location of the top elevation of the Jackpile and the bottom elevation of the Dakota. The Jackpile-Dakota Contact Surface is currently visible along the perimeter of Pit 1. Based on the three-dimensional geologic model of the Jackpile using data from outcrop exposures and bore logs for monitoring wells, exploration bores, and water supply wells (see Section 5.2 in INTERA, 2015), the lowest elevation of the Contact Surface within Pit 1 is at approximately 5,924 ft amsl, roughly 70 ft above the current lowest pit floor elevation. On a regional scale, the Contact Surface has its highest elevations in the south and trends downward to the northwest or north/northwest at a dip angle of about 1 to 2 degrees (INTERA, 2015; **Figure 2**). Thus, the Jackpile, and the overlying Dakota, slope downward in a direction that is roughly opposite to the regional direction of Jackpile groundwater flow (compare **Figures 1** and **2**).

Differences between Jackpile groundwater heads and the Contact Surface can drive flow of Jackpile groundwater into the overlying Dakota. If, at a given location, the Jackpile groundwater head is lower than or equal to the Contact Surface elevation, then the groundwater is under unconfined conditions and there is little to no driving force for flow from the Jackpile into the Dakota. If at a given location, the Jackpile groundwater head is greater than the Contact Surface elevation, then the groundwater is under confined conditions and there is a potential driving force for local flow from the Jackpile into the Dakota. Based on data for Jackpile top elevation and 2011-2013 groundwater heads (INTERA, 2015, 2017, 2019), confined conditions extend across the JJ mine area (green overlay color in **Figure 3**) whereas unconfined conditions extend across most of the Jackpile-Paguate and St. Anthony mines (purple overlay color in **Figure 3**). Unconfined conditions in the Jackpile at St. Anthony Mine are caused mainly by the gradual rise in the Jackpile's bottom elevation and, locally, by the Pit 1 hydraulic sink. The Jackpile is unsaturated southeast of unconfined conditions (**Figure 3**), including at the St. Anthony MW-12a and MW-12b monitoring wells (**Figure 1**), because the bottom elevation of the Jackpile is higher than groundwater heads to the north and northwest (**Figures 2** and **3**).

Confined conditions can exist in Jackpile groundwater because it is bounded by adjacent layers with much lower hydraulic conductivity that act as confining layers. The Brushy Basin mudstone that underlies the Jackpile acts as the lower confining layer because the mudstone has a much lower hydraulic conductivity than the Jackpile (INTERA, 2015). The upper confining layer comprises the kaolinitic cements in the upper Jackpile and, where present, a mudstone or clay interval at the bottom of the Dakota (INTERA 2015). The upper part of the Jackpile has kaolinitic cements that fill the pore space and could create a confining interval within the Jackpile itself (Schlee and Moench, 1961; Kittel, 1963; Sections 3.3.4 and 5.1.1 in INTERA, 2015). Based on the observed, confined conditions for Jackpile groundwater at some monitoring wells, we infer that these cements and the mudstone at the base of the Dakota, where present, have a lower vertical and horizontal hydraulic conductivity than that in the rest of the Jackpile.

The Dakota is unsaturated where it surrounds Pit 1 and to the south (INTERA, 2015). While there are no monitoring wells screened in the Dakota to provide measurements of Dakota groundwater heads at the St. Anthony or JJ mine sites, saturated conditions were observed in borings advanced through the Dakota to the northwest of Pit 1. Bore logs and field notes for JJ mine monitoring wells MW-1, MW-2, and MW-5 (**Figure 1**), located between 4,500 to 7,600 feet northwest of Pit 1, identified saturation in the Dakota during drilling in 2008 and 2012 (see Appendices A and C in INTERA, 2009 and Appendix A in INTERA, 2017). Field notes for the Jackpile monitoring wells installed at the St. Anthony mine revealed evidence that the Dakota was saturated at MW-8 during drilling in 2007 (INTERA, 2007). MW-8 is the St. Anthony monitoring well nearest to the JJ mine and is located about 1,900 feet northwest of the north Pit 1 wall (labeled as STA-MW-8 in **Figure 1**). This observation is expected based on the dip of the Dakota and incision by Meyer Draw. The Dakota, like the Jackpile, dips to the north-northwest at a 1-to-2-degree angle (**Figure 2** and INTERA, 2015). The dipping Jackpile and Dakota strata are highest to the southeast and lowest to the northwest as seen in the southeast to northwest geologic cross-section in **Figure 4** from southeast of Pit 2 through Pit 1 to northwest of JJ mine monitoring wells JJ-MW-03 and JJ-MW-04.

Groundwater Flow Models of Post-Closure Conditions

To evaluate the potential for flow of poor-quality groundwater from the Jackpile to the Dakota following a partial backfill of Pit 1 at elevations above and below the Contact Surface, we considered results from three different predictive models of groundwater flow in the Jackpile sandstone:

- 2015 Groundwater flow model developed for the St. Anthony Stage 2 Report (INTERA 2015)
- 2017 Groundwater flow model created for the JJ mine Stage 1 Investigation Report (INTERA 2017) that was based on the 2015 groundwater flow model. At NMED's request, INTERA developed a single comprehensive model for use in assessing conditions at both the St. Anthony and JJ mines.
- 2019 Probabilistic groundwater uncertainty analysis carried out for the JJ Mine Stage 2 Abatement Plan that incorporated uncertainty in model inputs into model predictions (INTERA 2019) and was based on the 2015 and 2017 groundwater flow models.

2015 Groundwater Flow Model

INTERA conducted groundwater flow modeling to determine groundwater flow from Pit 1 after completion of the proposed reclamation described in the St. Anthony Stage 2 Report (INTERA, 2015). The key reclamation elements that affected post-closure groundwater flow were the partial backfill of Pit 1 above the Contact Surface, which would eliminate the evaporative sink, and the partial backfill of Pit 2 to eliminate recharge to the Jackpile. INTERA developed a deterministic modeling approach to simulate post-backfill groundwater flow using a four-step process:

1) Carry out a deterministic calibration to observed groundwater heads that represented steady flow conditions for conditions at that time (2011 to 2013) to obtain defensible estimates of model parameters (calibration model);
2) Simulate post-closure groundwater heads after removing the evaporative sink in Pit 1 and the recharge area in Pit 2;
3) Implement particle tracking to show where groundwater from within Pit 1 will migrate (predictive model); and

4) Carry out a sensitivity analysis to determine whether the final fate of Pit 1 groundwater would change with different model inputs.

The numerical models developed from this process represent all the driving forces and hydrogeologic features that were described in Section 5.1 of INTERA (2015) as the most important controls on current and future groundwater flow within the area of interest. Key features and assumptions of the modeling process include:

- Groundwater flow in the Jackpile was simulated using a one-layer, two-dimensional numerical model. The single model layer used to simulate the entire Jackpile did not allow vertical flow into or out of the Jackpile. As such, groundwater flow from the Jackpile into adjacent units was assumed to be negligible.
- Groundwater inflows to the Jackpile comprised: 1) lateral inflow at the north boundary and a small segment of the west boundary; 2) recharge at Pit 2 and several small locations north of the Jackpile pit in the Jackpile-Paguate Mine; and 3) surface water discharge to groundwater along a reach of the Rio Paguate.
- Regional groundwater outflows from the Jackpile were limited to groundwater discharge to the Rio Moquino and Rio Paguate surface water in the vicinity of the Jackpile Mine, tamarisk-driven evapotranspiration in Meyer Draw and Bohart Canyon, and evaporation-driven removal of water from Pit 1.
- Groundwater flow under current conditions (Pit 1 open and functioning as an evaporative sink) was assumed to be steady flow because groundwater heads at the JJ and St. Anthony Mines were observed to have only small changes. The lack of any trends observed in Jackpile groundwater heads at the monitoring wells for both mines indicated that there were no time-varying stresses on the Jackpile groundwater flow system at that time.
- The predictive groundwater flow model simulated steady-state flow and particle tracking under post-closure conditions that eliminated the evaporative sink in Pit 1 and recharge in Pit 2 through partial backfilling of the pits. The top of Pit 1 backfill was set to be at roughly 5,976 ft amsl, about 50 ft above the lowest point in the Contact Surface within Pit 1 (approximately 5,924 ft amsl).
- The Jackpile was assumed to have a uniform hydraulic conductivity; that is, hydraulic conductivity did not vary with location.
- The calibration process used observed groundwater heads from the Jackpile-Paguate, JJ, and St. Anthony Mines to estimate values of hydraulic conductivity and parameters for the boundary conditions that best fit the observed data.
- The modeling section in INTERA (2015) and the model input and output files were previously reviewed by Dr. J. Marcoline, NMED, to "*…ensure that NMED was comfortable with the hydrologic model, and we were in agreement with that model prior to approval of the Stage 2 Plan*" (New Mexico Water Quality Control Commission, 2017).

2017 Groundwater Flow Model

The approach presented above was also used to investigate the post-reclamation impacts for the JJ Mine to support the Stage 1 Investigation for the JJ No. 1/L-Bar Mine (INTERA, 2017). The only major difference between the modeling performed in 2015 and modeling performed in 2017 was that the particles used for particle tracking originated within the JJ Mine site instead of St. Anthony Mine's Pit 1.

2019 Probabilistic Groundwater Uncertainty Analysis

A calibration-constrained uncertainty analysis was carried out for the JJ Mine Stage 2 Plan based on the 2017 groundwater flow model. Instead of a single set of deterministic calibrated model parameters, the null space Monte Carlo method (Watermark Numerical Computing, 2015; INTERA, 2019) was used to produce 440 sets of equally well-calibrated stochastic model parameters. Each set of calibrated model parameters, referred to as a "realization," was used to predict groundwater flow and particle tracking from JJ Mine after closure. This process yielded 440 predictive model results that were used to estimate the most likely flow paths based on model parameters that honored the observed groundwater heads and flow directions (INTERA, 2019).

Predicted Groundwater Heads at Pit 1 for Post-Closure Conditions

Results from the three different predictive groundwater models for the Jackpile demonstrate that if Pit 1 is backfilled to above the Contact Surface, the predicted elevation of Pit 1 groundwater will be above the Contact Surface within Pit 1. The Jackpile groundwater heads in Pit 1 were predicted to reach:

- 5,966 ft amsl using the INTERA (2015) groundwater flow model developed for the St. Anthony Stage 2 Report
- 5,966 ft amsl using the updated groundwater flow model created for the JJ Mine Stage 1 Investigation report (INTERA 2017)
- 5,958 to 5,969 ft amsl based on the probabilistic groundwater uncertainty analysis carried out for the JJ Mine Stage 2 Abatement Plan (INTERA, 2019) that incorporated uncertainty in model inputs into model predictions.

In all cases, backfilling Pit 1 according to the prior St. Anthony Mine Stage 2 Abatement Plan will lead to future Pit 1 groundwater heads that will exceed the lowest elevation of the Contact Surface. Consequently, poor-quality groundwater within Pit 1 would migrate into the unsaturated Dakota along all Contact Surface elevations within Pit 1 that are less than the 5,958 to 5,969 ft amsl range estimated from the INTERA (2019) calibration-constrained uncertainty analysis.

Volumetric Water Flux from the Jackpile to Dakota

Assuming a backfill above the Contact Surface, the rate of Jackpile groundwater flux into the Dakota in Pit 1 will depend in part on two factors: the vertical hydraulic gradient between the Jackpile and the Dakota and the vertical hydraulic conductivity of the backfill materials. To avoid vertical flow into the Dakota, the pit backfill at and just below the elevation of the Contact Surface must have a significantly lower hydraulic conductivity than the horizontal hydraulic conductivity within the lower backfill and the surrounding Jackpile, i.e., a semi-horizontal hydraulic barrier must be constructed within the pit that vertically extends to the Contact Surface at a minimum. Using Darcy's Law and some reasonable assumptions described below, INTERA has estimated the potential volumetric water flux from the Jackpile across a hydraulic barrier along the Contact Surface within Pit 1 to the Dakota for a range of vertical hydraulic conductivity values.

Darcy's Law can be used to estimate the flux across the entire Pit 1 hydraulic barrier under steady flow conditions. The law states that the volumetric flux across an area equals the product of the hydraulic conductivity and the hydraulic gradient. To estimate the flux across the entire Pit 1 hydraulic layer, we assume that the average elevation of the Contact Surface within Pit 1 is approximately 5,935 ft amsl and that the hydraulic barrier is ten feet thick. If we use a final Jackpile groundwater elevation of 5,966 ft amsl (predicted final Pit 1 groundwater head in INTERA, 2015 and 2017 and within the probabilistic range of 5,985 and 5,960 ft amsl predicted by INTERA, 2019), the hydraulic gradient between the post-closure Jackpile groundwater and the unsaturated Dakota is 31 ft divided by the 10-ft-thickness of the hydraulic barrier, which gives a value of 3.1 ft/ft (**Attachment A**). The gradient is calculated with the assumption that the Dakota is unsaturated across most of the Pit 1 hydraulic barrier. The area of the Contact Surface within Pit 1 is about 40 acres or about 1.8 million ft^2.

The area and hydraulic gradient values above were used with a wide range of vertical hydraulic conductivity values in Darcy's Law to estimate a range of volumetric water fluxes from the Jackpile to the Dakota through the hydraulic barrier (**Attachment A**). The vertical hydraulic conductivity was allowed to range from a value of 10^{-11} centimeters per second (cm/s) to 10^{-4} cm/s to provide a wide range of estimated flux rates (**Attachment A**). The Jackpile horizontal hydraulic conductivity is about 3.5 x 10^{-5} cm/s. The range of vertical hydraulic conductivities used in the calculation was chosen based on the uncertainty in the hydraulic conductivity values for:

- A hypothetical construction of an engineered hydraulic barrier,
- The contact or seam between the pit wall and the hypothetical hydraulic barrier, and
- The areas of the natural confining layer within the pit walls that may have been damaged when Pit 1 was constructed, i.e., excavation damage zone (Stantec, 2021).

In brief, Darcy's law is used to calculate the water flux in cubic meters per year across a Pit 1 confining unit with reasonable thickness and an expected average elevation difference of 31 feet for the entire confining unit area of about 1.8 million square feet. The estimated groundwater flux from the Jackpile within Pit 1 to the overlying backfill that is adjacent to the Dakota is roughly 1.6 million liters per year for the vertical hydraulic conductivity value of 10^{-8} cm/s, which is near the mid-point of the range of values INTERA evaluated, equivalent to a flux of 2.8 x 10^{-5} feet per day (**Attachment A**). Thus, constructing a hydraulic barrier within Pit 1 with a vertical hydraulic conductivity value of 10^{-8} cm/s will lead to a large volumetric flux of poor-quality Jackpile groundwater into the Dakota in Pit 1. This vertical hydraulic conductivity value is very conservative because it is unlikely that the combination of the hydraulic barrier, its contact with the pit wall, and the excavation damage zone in the surrounding Jackpile would all uniformly have such a low hydraulic conductivity value.

Increasing the thickness of the hydraulic barrier will cause a proportional decrease in the vertical hydraulic gradient as well as the vertical water flux from the Jackpile to the Dakota. However, doubling the thickness will only halve the vertical flux. Thus, barrier thickness has a relatively small impact on reducing flux compared to the much larger impact from reducing vertical hydraulic conductivity, which can vary by orders of magnitude.

Once the Jackpile groundwater enters the currently unsaturated Dakota along the perimeter of Pit 1, INTERA's assessment indicates it will flow through the unsaturated Dakota until it reaches the area where the Dakota is saturated. Gravity will drive the Jackpile seepage to flow along the Contact Surface, following the downward dip, until it reaches the Dakota's saturated area currently located somewhere between Pit

1 and St. Anthony monitoring well MW-8 (**Figure 4**). This pattern of flow from the Jackpile into the Dakota will continue for some time, increasing the extent of Dakota saturation, until equilibrium is reached between head in the Jackpile groundwater and head in the Dakota groundwater. Based on our review of water supply records from the New Mexico State Engineer's Office, there are wells located to the north of St. Anthony Mine that are screened across, and extract water from, multiple sandstone intervals, including the Dakota, Jackpile, and deeper sandstones. As a result, even with the construction of a hypothetical hydraulic barrier, poor-quality Jackpile groundwater from Pit 1 could enter the Dakota and migrate to the north/northwest where the Dakota is saturated and potentially be captured by pumping wells.

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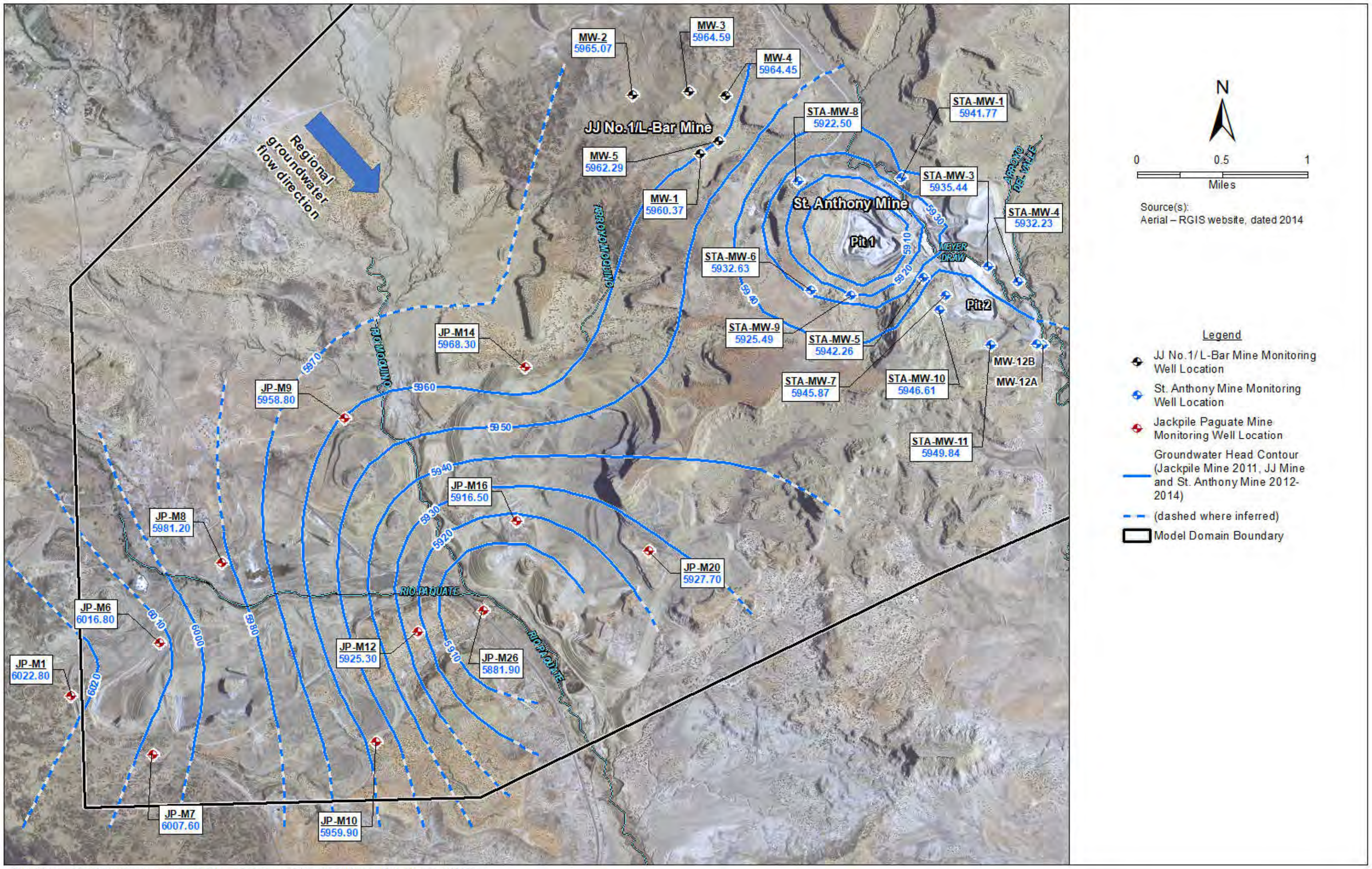

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Figure 1. Estimated Contours for Groundwater Heads under 2011-2013 Conditions (adapted from Figure 6-5 in INTERA, 2017).

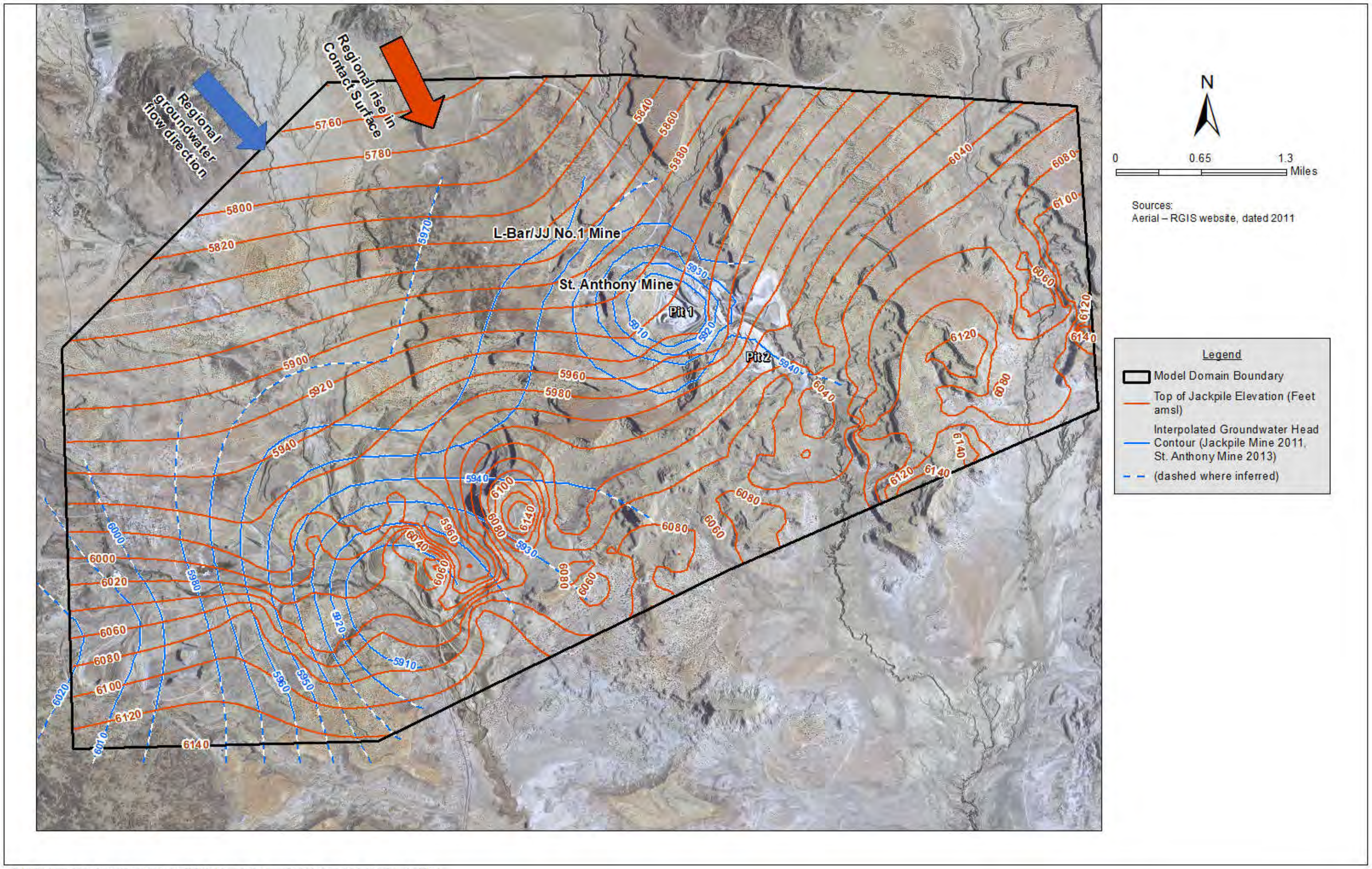

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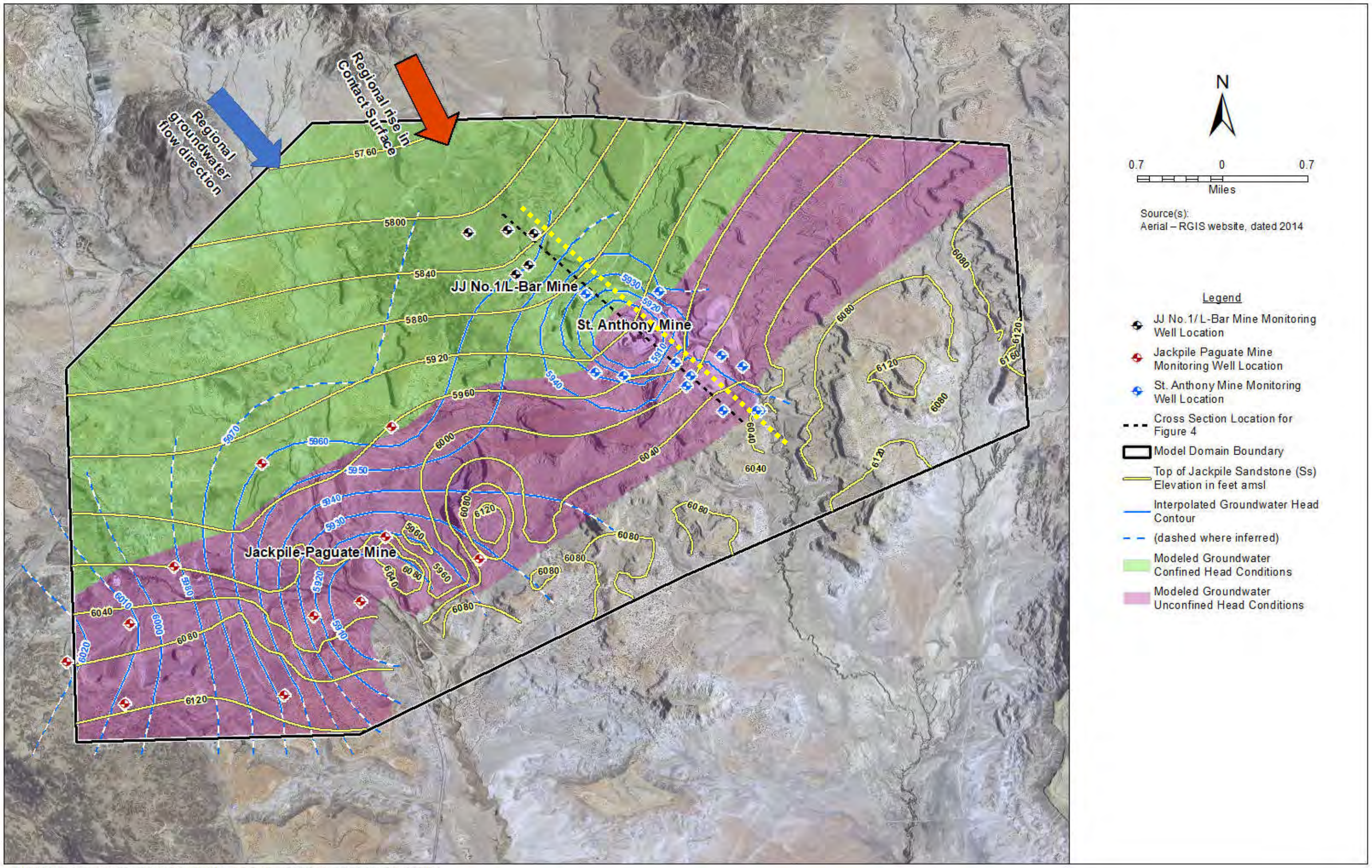
Figure 2. Top Elevation of Jackpile Sandstone and Estimated Contours for Groundwater Heads under 2011-2013 Conditions (adapted from Figure 5-15 in INTERA, 2015).



Source(s):
Aerial – RGIS website, dated 2014

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Figure 3. Top Elevation of Jackpile Sandstone, Estimated Contours for Groundwater Levels, and Estimated Areas with and Confined and Unconfined Groundwater under Current Conditions (adapted from Figure 6-7 in INTERA, 2017). Shows location of Figure 4 cross-section.

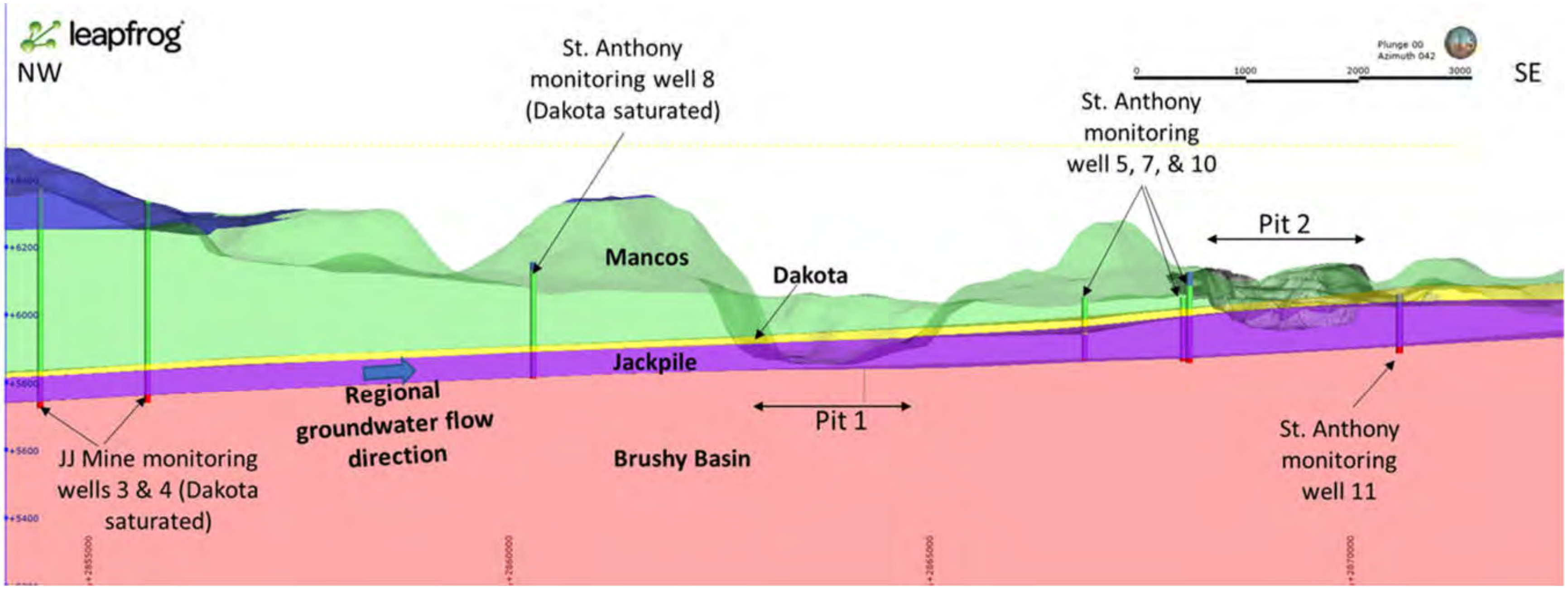


Figure 4. Cross-Section from Leapfrog Geologic Model Showing Dip in Dakota and Jackpile Sandstones in the SE to NW Orientation across St. Anthony and JJ Mines. Cross-section location shown in Figure 3. Regional Jackpile groundwater flow is from left to right. If Jackpile groundwater seeps into unsaturated Dakota at Pit 1, it will flow downdip from right to left.

Attachment A. Calculation Sheet for Jackpile to Dakota Flux within Pit 1 after Closure

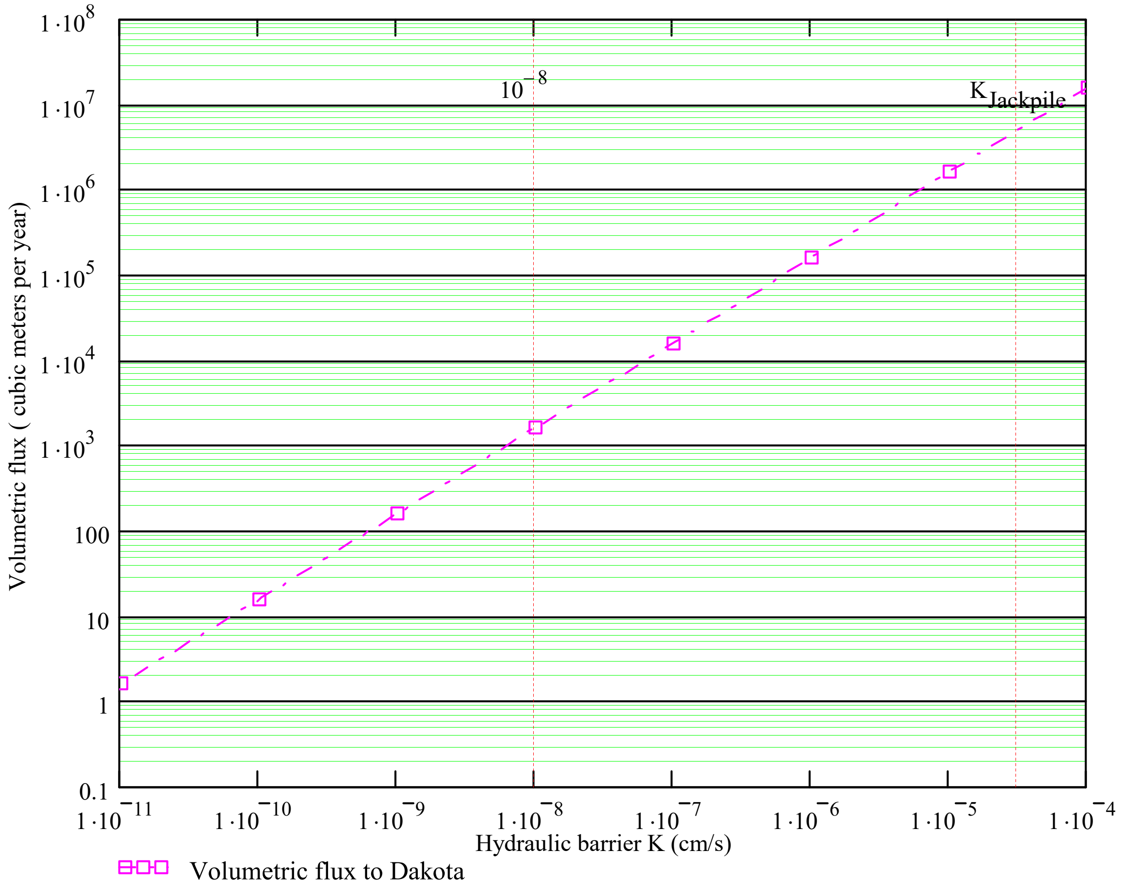
Compute volumetric flux from Jackpile SS to Dakota SS (Qz) given expected mean head difference of 31 ft (deltah) across a hydraulic barrier that spans the width of Pit 1 with a 10-ft thickness (b) for a range of vertical K values (K_{HB}).

K units for hydraulic barrier are in cm/s. K range was chosen to show flux range from very small to very high. For illustration purposes, the minimum feasible K value for hydraulic barrier was assumed to equal to 10^{-8} cm/s.

$i := 0, 1 .. 7$ $\quad K_{HB_i} := 10^{-4-i}$ $\quad K_{Jackpile} := 3.175 \cdot 10^{-5}$ $\quad deltah = 31\,ft$ $\quad b := 10 \cdot ft$

Area of Jackpile - Dakota contact within Pit 1 (from Stantec): $A = 1.755 \times 10^{6}\,ft^{2}$

$$Qz_i := A \cdot \frac{deltah}{b} \cdot \left(K_{HB_i} \cdot \frac{cm}{s} \right)$$



Stantec

Memo

To:	Mr. Lance Hauer United Nuclear Corporation	From:	Jason Cumbers, PE Fort Collins, CO
File:	233001363	Date:	November 4, 2021

Reference: Evaluation of Constructing a Hydraulic Barrier to Prevent Vertical Groundwater Migration in St. Anthony Pit 1

The reclamation approach for the St. Anthony Mine (“Site”) presented in the 2019 Closeout Plan (Stantec, 2019) and INTERA Stage 2 Report (INTERA 2015) included partial backfill of Pit 1 to an elevation above the interface between the Jackpile Sandstone of the Morrison formation (Jackpile) and the overlying Dakota Sandstone (Dakota) (Jackpile-Dakota Interface). Subsequent design efforts and groundwater modeling identified that this approach would result in groundwater rising to an elevation above the interface of these formations, resulting in groundwater migration from the pit into the overlying Dakota (INTERA, 2021).

At UNC’s request, Stantec evaluated the feasibility of constructing a hydraulic barrier within Pit 1 to prevent groundwater from migrating from the Jackpile to the Dakota should the backfill elevation exceed the Jackpile-Dakota Interface. This memo analyzes the technical feasibility of constructing such a hydraulic barrier given conditions at the Site and includes a review of similar assessments and technologies used at other sites. This report also evaluates the feasibility, limitations, and safety risks associated with attempting to construct such a hydraulic barrier. Ultimately, Stantec concludes that the construction of such a hydraulic barrier would be technically infeasible and would, in fact, represent an unprecedented engineering exercise.[1]

1.0 BACKGROUND

Prior to the development of Pit 1, groundwater was confined to the Jackpile by an overlying natural low permeability layer, comprising kaolinitic cements in the upper Jackpile and where present, a shale interval at the bottom of the Dakota (INTERA 2015). The development of Pit 1 for mining removed this confining layer within the pit area and disturbed the layer for some distance beyond the pit walls causing an extended fracture zone radiating outward from the pit wall.

The photo in Figure 1 shows the approximate location of the contact between the Dakota and the Morrison formations on the west highwall of Pit 1. The elevation of the base of the Dakota is between approximately 5945 and 5924 feet and averages 5935 feet above mean sea level (ft amsl). The Jackpile begins below that elevation and dips to the north one to two degrees.

The 2019 Closeout Plan proposed a backfill elevation in Pit 1 of at least 5976 ft amsl (Stantec, 2019). According to modelling, backfilling to this elevation would eliminate the hydraulic sink in Pit 1 and establish a “flow-through” system in the Jackpile. Subsequent predictive groundwater models determined that the Jackpile groundwater levels in Pit 1 would rebound between 5958 to 5969 ft amsl long-term (INTERA 2021). Groundwater rebound in this range tops the base of the Dakota. Accordingly, without confined conditions beneath the Jackpile-Dakota Interface, backfilling to, or above, the groundwater rebound level would allow

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[1] This memo uses the term “hydraulic barrier” rather than “confining layer” to avoid confusion with hydrogeologic concepts for confined and unconfined aquifers and the geology that confined the Jackpile pre-mining.

local saturation of the Dakota by the poor-quality water currently expressed in Pit 1 and naturally present in the groundwater in the Jackpile (INTERA, 2021).

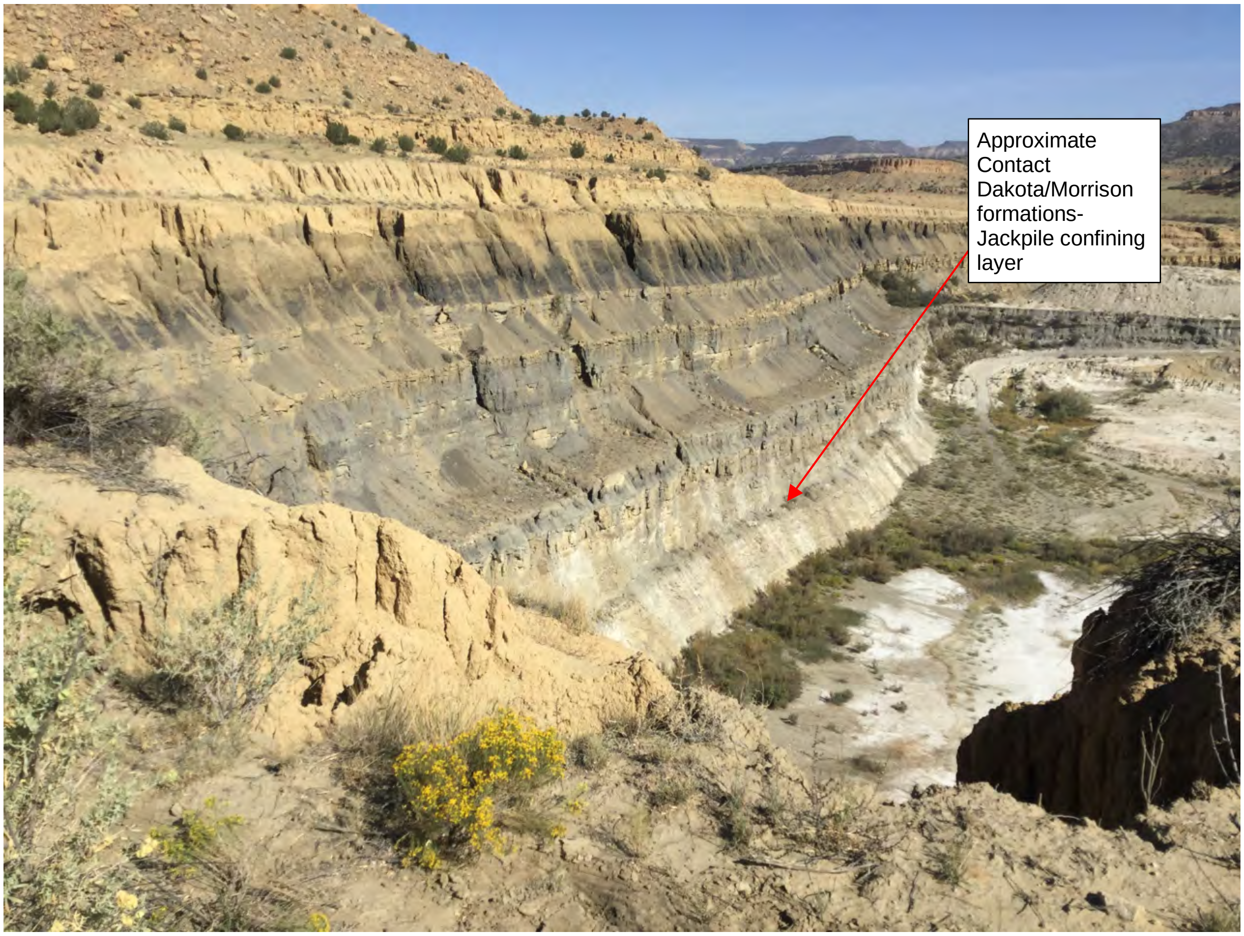

Figure 1 – St. Anthony Pit 1, West Highwall Dakota-Jackpile Contact (view to the North)

2.0 CONSTRUCTION OF A HYPOTHETICAL HYDRAULIC BARRIER

Currently, confining conditions do not exist within the open excavation of Pit 1. To backfill Pit 1 above the Jackpile-Dakota Interface and avoid groundwater rebound into the Dakota, a hydraulic barrier would need to be constructed to establish the requisite confining conditions. Using Darcy's law, INTERA performed calculations to predict the vertical flow of water across a hydraulic barrier based on different assumed values of vertical hydraulic conductivity (K) ranging from 10^{-11} centimeters per second (cm/s) to 10^{-4} cm/s (INTERA 2021). Based on INTERA's calculations, construction of a hydraulic barrier with a long-term K value of 10^{-8} cm/s results in over a million liters of water flowing into the Dakota each year. A K value of 10^{-8} cm/s reflects the approximately median value evaluated by INTERA and, as discussed below, the lower end of reasonably achievable K values in engineered hydraulic barriers. According to INTERA's calculations, a K value for a hydraulic barrier of 10^{-10} cm/s (which is two orders of magnitude less permeable than current best practices) would still result in flux to the Dakota of roughly 20 cubic meters per year. From an engineering and constructability perspective, it is impossible to construct a hydraulic barrier that would prevent upward groundwater flux into the Dakota in any scenario involving backfilling above the Jackpile-Dakota Interface.

Notwithstanding this impossibility, and for purposes of this evaluation, Stantec explored constructing a 10-foot-thick, low-permeability layer with a long-term K value of 10^{-8} cm/s in Pit 1. INTERA's calculations were based on the hydraulic barrier covering the entire top of the Jackpile which would require a barrier of approximately 1.76 million square feet. It is important to note that construction of a thicker barrier layer would only serve to delay the time in which poor-quality groundwater would reemerge into the Dakota, rather than prevent recharge altogether. The layer would have to be located within the pit backfill between approximate elevations of 5925 to 5935 ft amsl, near the top of the Jackpile, in an effort to maintain the rebound groundwater elevation below the base of the Dakota. Figure 2 illustrates the conceptual design for the backfill with a low-permeability hypothetical hydraulic barrier layer.

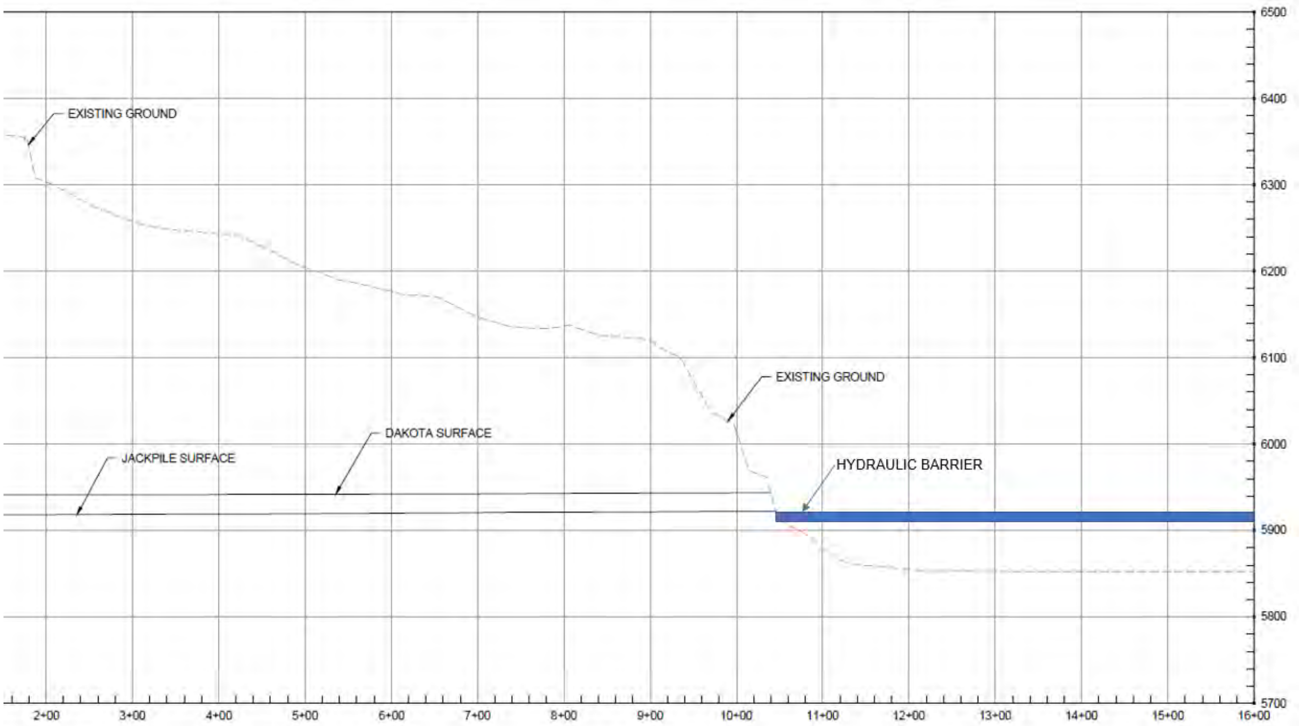

Figure 2 – Conceptual Cross Section of Pit 1 Showing Hypothetical Hydraulic Barrier

Stantec evaluated a series of different potential design elements for backfilling Pit 1 with a hydraulic barrier. As described above, obtaining a zero-flux hydraulic barrier is not possible. At best, with a K value of 10^{-8} cm/s, a hydraulic barrier would still allow roughly 1.6 million liters per year of poor-quality groundwater flow into the Dakota long-term. To construct a hydraulic barrier with a long-term K value at, or lower than, 10^{-8} cm/s, the following four components would be required:

1. **Repair of the fracture zone:** resealing the low-permeability layer from the pit walls back into the Jackpile, where the formation has been affected by pit development, drilling and blasting;
2. **Prevention of differential settlement:** engineering and constructing the pit backfill so as to prevent settlement of the backfill material and the creation of preferential pathways that would increase the conductivity of the hydraulic barrier;
3. **Construction of a horizontal hydraulic barrier:** within the Pit 1 backfill sequence with a K value of $1x10^{-8}$ cm/sec or less;
4. **Sealing of the Perimeter:** of the pit where the proposed horizontal low-permeability layer would contact the near-vertical walls at the contact with the Dakota formation.

As discussed below, these conditions cannot be managed to achieve a long-term K value at 10^{-8} cm/s with a reasonable degree of certainty, much less a K value two orders of magnitude lower that would be necessary to bring the flux closer to zero. Even if it were possible to achieve these four pre-requisites, the confinement of groundwater locally in the pit backfill will not guarantee that water does not reemerge somewhere beyond the perimeter of the pit. The Stage 2 Report (INTERA, 2015) indicates that the effective radius of the groundwater sink extends up to about 0.5 mile from the center of the pit. Therefore, it is plausible that constructing a low-permeability hydraulic barrier in the pit could result in groundwater re-emerging elsewhere in the Dakota, beyond the influence of an engineered solution within the pit.

These four hydraulic barrier prerequisites are assessed in the next section.

3.0 HYDRAULIC BARRIER PREREQUISITES

In assessing the four components necessary to achieve a viable hydraulic barrier in Pit 1, Stantec reviewed a series of potential technologies with applications analogous to construction of a hydraulic barrier within the Jackpile at Pit 1. Each technology considered has drawbacks and limitations that would rule them out as potential alternatives at St. Anthony. Each also would require rockfall mitigation to allow workers to safely access the lower pit walls. In the case of the potential technologies described below, additional precautions would be required for working adjacent to the highwalls for longer durations and outside of heavy equipment. These technologies are summarized in the following sections.

3.1 Repair of the Fracture Zone

A primary consideration with construction of a hydraulic barrier at the Site is the need to repair the damage done to the Jackpile formation in the rock mass near the pit walls. Due to the drill-and-blast methods and mechanical excavation used to develop the pit, the low-permeability layer at the top of the Jackpile formation has been disturbed to some unknown horizontal distance back into the walls around the entire perimeter of the pit, creating a fracture zone. Because the fracturing that resulted from drilling and blasting has weakened the rock formation, the permeability of this layer is now controlled by the fractures within it to an undefined and variable distance back in from the walls of the pit. This means that, even if it were possible to engineer a horizontal low permeability barrier that could achieve an acceptably small flux to the Dakota, if the pit were backfilled above the lowest elevation of the Dakota, groundwater would still rise and reach the Dakota at some distance from the pit as the cone of depression is eliminated. Furthermore, there is no practical way to evaluate the extent of the fracturing within the Jackpile extending back in from the walls in all directions without extensive drilling and sampling of the formation. This would result in further modified permeabilities within the rock mass. The USACE manual on Grouting Technology (USACE, 2017) indicates that clean rock fractures can be reduced to about 0.1 Lugeon for special grouting applications, but this would still only result in a grouted K of the rock mass on the order of $1x10^{-6}$ cm/sec.

To estimate the extent of formation damage during pit development, Hoek and Karzulovic (2000) propose a number of relationships that relate the height of highwall benches to the extent of damage. These relationships depend upon the type of blasting that took place on the wall. The distance from the face of the wall to the extent of the damaged rock zone varies from 0.5 for a carefully controlled blast with a free face, to 2.5 for large, confined production blasts. To estimate the extent of damage surrounding the Pit 1 highwall, Stantec assumed that the highwall was a production blast completed prior to excavation of the open faces for each subsequent excavation, as was typical for mines at the time. Assuming this scenario, and using the calculation described by Hoek, the damaged zone in Pit 1 could extend as much as 2.5 times the height of the individual benches in from the highwall, or as shown in Figure 3, T (thickness of blast damage) could extend up to 2.5H.

Benches on the St. Anthony Pit 1 highwall range in height from 30 to 90 feet tall, indicating that damage to the rock could extend 75 to 225 feet past the highwall into the formation. However, this distance of influence will vary significantly based on changes in the geology. Factoring in the effects of long-term softening of the rock over the 45 years since the pit was developed lends further support to the viability of this estimate.

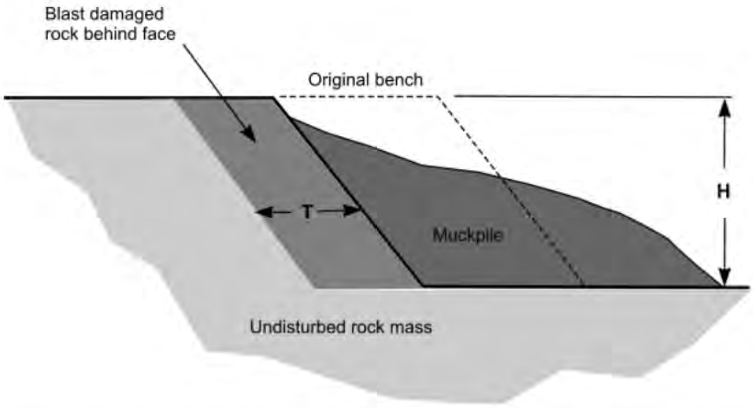

Figure 4: Diagrammatic representation of the transition between the in situ rock mass and blasted rock that is suitable for digging.

Figure 3 – Blast Damaged Zone and Bench Height (Hoek, 2012)

The actual fracture damage in the rock layers would also vary as the distance from the highwall increases. Hoek (2012) proposes a damage factor for rock impacted by blasting ranging from 0 for undamaged and 1 for highly damaged. For the Pit 1 highwall, the damage factor at the blasting location (the existing wall) would be 1 (Hoek, 2012) and would decrease as the distance from the wall increases. Repairing fractures in rock can be attempted by grouting, with quality control assessed based on the grout takes during a grouting operation. However, Stantec does not consider this to be a feasible option at St. Anthony due to the impracticality of conducting an investigation that would accurately define the extent of fracturing, in addition to the potential modifications to rock permeability that would be caused by an evaluation.

The practicality of attempting to achieve a K of 1x10^{-8} cm/sec by grouting the damaged, fractured zone is considered infeasible because, per the USACE reference above, grouting fractures to such a low K level isn't practically achievable. The K level that could be obtained realistically is likely higher than what would be required due to the challenges with grouting at depths of 150 feet from the highwall or from angled grout holes from the lowest bench 40 to 70 feet deep.

3.2 Prevention of Differential Settlement

A hypothetical hydraulic barrier of 10 feet thickness placed over 70 feet of pit backfill would be subject to significant differential settlement that could deform the barrier and lead to cracking and reduced long-term hydraulic performance of the material. This cracking would manifest itself in increases in the K value of the layer which would lead to additional water seeping past, or through, the engineered hydraulic barrier. The pit backfill material at St. Anthony consists of soil and waste rock from the existing waste piles which contain a range of particle sizes, from silts and clays to large boulders, on the order of 12 to 36 inches in diameter. Specific compaction control and methods would be required for pit backfilling to manage settlement of the placed backfill. These controls would typically consist of 3- to 5-foot-thick lifts for materials of this size range to manage the large fragments of waste rock, compacted with large vibratory rollers.

Using a similar approach for another pit backfill project at a uranium mine with total fills on the order of 300 to 400 feet deep, Stantec predicted total settlements on the order of 9 to 13 feet, with differential settlements on the order of 1 to 3 feet. In the case of St. Anthony for the hypothetical hydraulic barrier scenario described in this memo, for fills on the order of 75 to 100 feet, settlements on the order of 3 to 4 feet may be expected, with differential settlements expected to be about 1/3 of the total. Even 1 foot of differential settlement across a ten-foot-thick soil barrier layer would result in micro-fissures in the soil that would increase the K value over time and lead to unwanted upward flux through the fill, particularly with the upward gradient that would occur if the pit were backfilled. Even with tightly controlled backfill compaction methods for the placed mine waste, some settlement is expected due to the range of particle sizes within the mine waste and the larger layer thickness necessary to accommodate these materials during placement.

3.3 Construction of a Horizontal Hydraulic Barrier

If Pit 1 were backfilled to above the bottom of the Dakota formation, creating a low-permeability layer near the Jackpile-Dakota Interface would be a key requirement to prevent groundwater migration upward through the backfill material. Based on the laboratory testing conducted by Stantec in 2020 (DBSA, 2020), the existing borrow soils at the site that will comprise some of the backfill materials have saturated hydraulic conductivity (K_s) values ranging from 9x10^{-6} to 7x10^{-4} cm/s for specimens remolded to 90% of the standard Proctor values,. A compacted soil layer of up to 95 to 100% of the Proctor density of the soil would require modification either by soil mixing or grouting to extend the range of the materials toward the lower target K value.

Soil mixing is standard practice to modify soil materials and create a more impervious soil layer. Soils on the ground surface are mixed using standard earthwork equipment, like discs or rotomills, to engineer performance for a specific soil type. Research from Nevada, USA indicates that the addition of 6.5% bentonite by weight can decrease permeability of a sandy base soil by two orders of magnitude to 7.6x10^{-8} cm/sec (Albright, 1995). Since the compacted K of the borrow soil at the Site is higher than that required to mimic the expected K of the Jackpile, mixing these soils with imported bentonite during placement could decrease the K by several orders of magnitude to between 9x10^{-8} and 7x10^{-6} cm/sec. However, this method would not ensure a K value consistently equal to, or less than 1x10^{-8} cm/sec.

Jet grouting, or high-pressure injection of cementitious material through large diameter mixing augers, is commonly used to create low-permeable barriers in excavations, or to seal an area vertically to prevent horizontal flow. Historically, jet grouting has been used with some success to seal the base of deep excavations and prevent groundwater inflow (Cao et. al., 2019). In one case, for a bottom-grouted deep excavation, a 5m thick layer of grout resulted in a low-permeability barrier averaging $1.6x10^{-4}$ cm/s. Another example from a jet grouting specialty contractor (Geo-Foundations, 2013) demonstrates the ability to meet a $1.0x10^{-7}$ cm/s maximum target for jet grouted columns in a mixture of silts and sands. From an access perspective, because jet grouting is typically accomplished using drill rigs and can be done with angled holes, jet grouting could be extended to a vertical rock face, with the equipment sitting several feet from the face. Quality assurance of jet grouted columns is done via confirmatory drilling, sampling, and lab testing back through the columns upon completion. However, like soil mixing, jet grouting will not achieve a K value equal to, or less than, $1x10^{-8}$ cm/sec.

Geosynthetic clay liners (GCL), high density polyethylene (HDPE) liners, or linear low-density polyethylene (LLDPE) geomembrane liners, are commonly used to construct landfills, line ponds, or prevent infiltration from contacting waste materials. NMAC 20.6.7.17 requires that process and impacted stormwater containment impoundments have 60mil HDPE liners, leachate collection and leak detection systems. Similarly, RCRA Subtitle C landfill covers must include a natural or amended soil layer with a maximum K of $1.0x10^{-7}$ cm/s and a minimum 20-mil geomembrane liner (USEPA, 1991). It is commonly assumed for design purposes that all composite liners leak and that quality control during installation will reduce the number of holes in a liner, but typically between 1 and 20 holes per acre can be present in an installed liner (Giroud and Bonaparte, 1989). Obviously, this has a significant effect on the leakage rate through a composite liner; however, USEPA defines an “excellent” composite liner as one having a K_{sat} of less than $1.0x10^{-8}$ cm/s and fewer than 1 hole/acre with a hole size of less than $0.1cm^2$. This means that, even if it were possible to construct a hydraulic barrier at St. Anthony that achieved a K value aligned with USEPA’s criteria for “excellence,” it would still permit over 1.6 million liters of poor-quality water to flow into the Dakota each year. Efforts to further reduce this volume would require achieving standards more stringent than USEPA’s requirements for hazardous waste landfills.

There are examples of projects in which synthetic liners are affixed to rock surfaces, or to concrete, using rock bolts and plinths, which would be required to affix liner to the highwall at the Site (Hore and Luppnow, 2015). One example found described approximately 20 million cubic meters of tailings proposed for placement as pit backfill with an HDPE liner and design of a drainage layer under the pit backfill (tailings) to collect leachate. In the case of St. Anthony, a synthetic liner could be installed near the desired K value for the horizontal layer. However, to prevent groundwater from escaping the liner perimeter, the seal would have to be designed and constructed to be waterproof. This would be extremely difficult to implement considering the uneven faces of the walls to which a liner would have to be attached and the expected groundwater pressures.

Stantec also reviewed examples of applications where synthetic liners were used to line pit walls with HDPE, LLDPE, or GCL liners and create a low permeability barrier. In one instance, a lined landfill facility was created from an exhausted gravel pit in Bristol, Virginia (Breitenbach, 2010). A similar liner application was applied at the Soledad Tailings Storage Facility in Honduras (Purdy et. al., 2017). While having the ability to tie the wall liner into a horizontal liner would create a nearly impervious barrier in the entirety of the pit and theoretically eliminate water flow around the horizontal hydraulic barrier, success of the perimeter seal would be entirely dependent on the ability to properly affix the liner to the uneven surfaces of the rock walls. Further, this option would not prevent migration of poor-quality groundwater from the Jackpile formation into the Dakota formation through the blast-damage zone into which the synthetic liner would be anchored.

3.4 Sealing of the Perimeter

Shotcrete is commonly used in earth retention applications to maintain stability of excavations, including below groundwater. Shotcrete is a cementitious mixture containing a percentage of aggregate that hardens as it cures. In some structural applications shotcrete is applied over reinforcing steel. Application of shotcrete would increase the stability of fractures on the wall faces at the Site and create a low permeability layer at the pit walls to reduce inflow of water. The mix design of the shotcrete would control the potential for water flow through the confining layer, with a lower “cement to water” ratio offering the best results. Mix designs for other applications have achieved K values as low as $1x10^{-7}$ cm/s (Barcena and Garcia-Sineriz Aitemin, 2008), but these values are not low enough for the objective at St. Anthony. Most applications of shotcrete, however, are for structural stability purposes and often temporary (e.g., rockfall, slope stability, structural improvements, tunnel stability). For this reason, the literature yielded only minimal information demonstrating shotcrete with a sealing function for the purpose of excluding groundwater on a long-term basis. While shotcrete on the wall faces may limit some inflow from the existing rock fractures, shotcrete will not help seal the horizontal layer to the vertical rock faces.

Another potential method to mitigate groundwater flow through backfill is construction of cutoff walls around the pit or perimeter. A low permeability cutoff wall consisting of a bentonite-soil mix or a cement-bentonite mix keyed into an existing subsurface confining layer could potentially seal a pit from groundwater flow into, or out of, the backfill (Evans, 1993). However, the use of cutoff walls using soil and bentonite are dependent on compatible site geology. In this case, cutoff walls would have to extend to depths of 100 to 200 feet, depending on bench accessibility, to key into or contact a confining layer and prevent groundwater from migrating beneath the cutoff wall and into the pit area. It is infeasible to construct a cutoff wall through this depth of hard rock geology due to equipment limitations and the inability to excavate through the rock. The Jackpile and the lower Dakota formations are too hard to allow for extension of a proper cutoff wall with the correct specifications to reach the existing low-permeability layer.

Engineering a hydraulic barrier at St. Anthony poses several intractable engineering problems. Grouting the fracture zone within the Jackpile behind the pit walls to cut off preferential flow pathways would not reduce the K to a low enough value to prevent flux. Similarly, due to the highly variable mine waste materials available for backfill, construction practices cannot guarantee the elimination of future differential settlement of a hydraulic barrier, leading to preferential flow paths caused by cracking, including of the perimeter seal during settlement. Available engineering techniques are not sufficient to construct a hydraulic barrier with a K value sufficiently low to eliminate groundwater flow. Further, no technologies were identified capable of constructing an effective horizontal barrier and sealing the perimeter to prevent flux to the Dakota. Therefore, Stantec concludes that the hypothetical approach of constructing a viable hydraulic barrier at St. Anthony to prevent impacts to the Dakota has a very low likelihood of success.

4.0 PROJECT AND LITERATURE REVIEW

To further assess the practical feasibility of constructing an industry standard hydraulic barrier in the present instance, Stantec researched whether any analog projects have been undertaken successfully. Stantec undertook an extensive literature review and relied on its own extensive mining and engineering expertise and team of experts with broad technical experience in a range of disciplines. Our mining group regularly solves complex problems related to hydrogeology, tailings, water and waste management and we deliver designs of both conventional and filtered tailings storage facilities. The Stantec St. Anthony project team consulted with several internal experts, including a Principal Geotechnical Engineer, Mr. Thomas Kelley, PE; a Principal Geochemist, Mr. Jim Finley, PhD; and a Principal Hydrogeologist, Mr. Walter Weinig, PG, in preparing this memo and for identification of analog project examples. Our experts have extensive understanding of the interactions between groundwater, pit design, mining, and waste containment. Our team's knowledge of the St. Anthony Mine site, the surrounding area, mining projects in New Mexico, and the greater US West, combined with our geotechnical, tailings and mine waste experience and complex hydrogeology and dewatering expertise, brings a wealth of experience and wide-ranging expertise to the project.

To evaluate the feasibility of constructing a viable hydraulic barrier within the proposed pit backfill, Stantec reviewed similar projects undertaken by Stantec staff globally and conducted an extensive literature review in an attempt to identify project analogs with problems similar to the St. Anthony project, i.e., creating a hydraulic barrier in an open pit mine. The summary of our literature review is included in Attachment A. Technical papers and articles for review were identified through searches of the following platforms: Springer Link, Engineering Village, Colorado State University Library system, Mine Closure conference proceedings, Tailings and Mine Waste conference proceedings, industry journals, Google Scholar, and the Google search engine. Searches focused initially on evaluating hydraulic barriers in open pit mine closure and open pit backfill applications, and then were expanded to include general mine closure, in-pit tailings and waste disposal, pit lakes, low permeability layers, shotcrete application, sealing of deep excavations, earthen dam core construction, and groundwater cutoff and control, along with general variations of these activities for thoroughness. Any mines or projects that were identified as potential analogs were researched further, along with the authors that researched the above topics and companies who worked on these types of projects, with the goal of identifying additional sources.

Articles identified through this process were then reviewed, logged (depending on their relevance) and summarized for easy reference. The only articles that were not considered as part of this review were a small number behind pay walls or that were not available in English. The review is considered exhaustive given the volume of sources reviewed and the quality of the platforms available to the reviewer. Stantec identified twenty-five project or technology examples for consideration as analogs to the St. Anthony problem. No examples were identified that included re-construction of a hydraulic barrier to control groundwater. Stantec has experience with the various potential technologies described in this memo for recreating hydraulic barriers, barrier walls, grouting, soil mixing, synthetic liners, ET soil covers and shotcrete.

In its analog project and literature review, Stantec identified no mining or other project (e.g., landfill project) where a hydraulic barrier with a permeability of less than 10^{-8} cm/s had been constructed successfully; therefore, we conclude that the potential to create such an engineered system at the Site is unproven. A more detailed review of several projects is included in Attachment B for reference. These examples show, among other things, that in several instances where construction of a hydraulic barrier was considered by highly experienced experts and mining companies, it was ultimately rejected as a viable option and not attempted due to engineering infeasibility and potential risks.

5.0 CONCLUSION

As discussed above, it is effectively impossible to construct a zero-flow barrier in Pit 1. Installing a hydraulic barrier in Pit 1 with even a K value less than 10^{-8} cm/s (the lower end of demonstrated technology) presents insurmountable construction obstacles. Mining and subsequent weathering has significantly degraded the geologic conditions in the rock behind the pit walls and created a fracture zone behind the pit walls with preferential pathways for vertical groundwater migration. The extent of the fracture zone is unknown and there is no technology to guarantee the complete sealing of the preferential pathways. Further, even if the fracture zone were grouted, there is a risk that containing the groundwater locally would result in re-emergence of the groundwater into the Dakota in a fracture zone, or other higher permeability area, beyond the area of improvement. Construction of a hydraulic barrier atop the substantial depth of variable fill will result in differential settlement over the design life of the barrier leading to cracks, preferential flow pathways, and a K value that would increase over time as the barrier layer settles, thus allowing greater flux.

Existing technology and construction activities have, at best, achieved long-term K values of 10^{-8} cm/s. Consistent with the adage “all liners leak,” and due to the expected upward gradient in this case, achieving this K value would still allow over 1.6 million liters of poor-quality water to enter the Dakota. Finally, current technology and construction practices would not ensure that a horizontal hydraulic barrier could be tied effectively into the irregular pit wall surfaces to prevent upward flow around the edges of the barrier. In short, there are no suitable practices or technology to satisfy all four of the engineering constraints required to isolate the Dakota from the poor-quality water in the Jackpile within Pit 1 if backfill elevation exceeds the Jackpile-Dakota Interface.

This conclusion is supported by Stantec’s literature and project review. No analog projects involving backfilling of an open pit mine with construction of a low-K hydraulic barrier to control upward migration of groundwater were identified, nor were any attempts to undertake such a project identified. Although there are technologies for constructing low-permeability barriers within a backfill, documentation of a successful application at a site analogous to St. Anthony could not be identified. Importantly, Stantec’s review did identify several examples where mine sites elected to maintain a hydraulic sink and management of groundwater expression with an evapotranspirative (ET) cover rather than proceed with unproven practices and risk future migration of poor-quality water away from the pit.

Accordingly, Stantec concludes that the construction of a hydraulic barrier to prevent the vertical migration of poor-quality water into the Dakota would be technically infeasible and would, in fact, represent an unprecedented engineering exercise.

Stantec Consulting Services Inc.

Attachment: Attachment A – Literature Review – Table of Project Examples
Attachment B – Summary of Key Project ExamplesAttachment A – Literature Review – Table of Project Examples
Attachment B – Summary of Key Project Examples

c. M. Mooney (UNC), C. Baker (PBL)M. Mooney (UNC), C. Baker (PBL)

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To: Mr. Lance Hauer, United Nuclear Corporation

From: Leslie Smith, Ph.D., P.Geo.

Date: November 9, 2021

Re: Assessment of Hydrogeologic Impacts of Backfilling St. Anthony Mine Pit 1, New Mexico

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In this memo, I provide my comments on the assessments undertaken to evaluate the potential hydrogeologic impacts of backfilling the St. Anthony Pit 1 to an elevation above the contact between the Jackpile Sandstone and Dakota Sandstone. The concept includes incorporation of a horizontal layer of very low hydraulic conductivity within the backfill to reduce upward flow of poor-quality groundwater from the Jackpile to the Dakota Sandstone. Two memos were reviewed to prepare this opinion:

INTERA - Pit 1 Backfill at St. Anthony Mine, Groundwater Rebound in the Jackpile Sandstone and Flow into the Dakota Sandstone, memo dated November 5, 2021.

Stantec - Evaluation of Constructing a Hydraulic Barrier to Prevent Vertical Groundwater Migration in St. Anthony Pit 1, memo dated November 4, 2021.

INTERA Memo on Groundwater Rebound in the Jackpile Sandstone

Two important features of the current hydrogeologic setting are relevant to the backfill concept. First, the existing groundwater flow pattern in the vicinity of Pit 1 reflects the effect of evaporative losses from the water pool located on the floor of the pit, creating a hydraulic sink in the regional potentiometric surface for the Jackpile Sandstone. On the pit floor, the water table is approximately at elevation 5850 feet. Second, beyond the immediate region of the open pit, kaolinitic cements in the upper part of the Jackpile Sandstone limit upward flow of poor-quality groundwater into the Dakota Sandstone. If Pit 1 is backfilled with mine waste materials to an elevation above the base of the Jackpile / Dakota contact, the potentiometric surface for the Jackpile will rebound and trend toward the pre-development condition set by the regional hydraulic gradient in the area.

It is understood that INTERA previously developed a three-dimensional groundwater model that indicates for a pit backfill elevation of 5975 feet, the potentiometric surface in the Jackpile would rebound to an approximate elevation of 5960 feet, a level well above the Jackpile / Dakota contact at elevation 5924 feet. This model prediction is considered reasonable, given the regional groundwater head map for the Jackpile Sandstone.

The rebound in the potentiometric surface will create a vertical hydraulic gradient driving seepage upward through both the pit backfill and the excavation damage zone located behind the pit wall. Two conditions are then established: 1) a hydraulic gradient that drives upward groundwater flow; and 2) a pathway through the backfill material that creates a hydraulic connection between the Jackpile Sandstone and Dakota Sandstone that currently does not exist. In addition, seepage will occur in the excavation damage zone behind the pit wall as the water table rebounds. The quantity of the seepage along each pathway will depend upon the vertical hydraulic conductivity of the backfill material and of the excavation damage zone, and any barriers that might be constructed to impede that flow.

INTERA, using a Darcy Law calculation, has estimated for different values of hydraulic conductivity the volume of seepage through the pit backfill incorporating the concept of a 10-foot thick barrier layer and sealing of the damage zone. I view this calculation as well suited to demonstrate the potential magnitude of the flow that could eventually enter the Dakota Sandstone. The Darcy law calculations suggest that a barrier constructed at the limits of demonstrated technology with a low vertical hydraulic conductivity of 10^{-8} cm/s, a seepage flow of about 1000 m^3/year from the Jackpile Sandstone to the Dakota Sandstone could occur.

INTERA indicates groundwater entering the unsaturated Dakota Sandstone for a backfilled pit can be expected to migrate as a wetting front in a down dip direction toward the region where the regional water table creates saturated conditions in the Dakota Sandstone. I concur with this conclusion.

Stantec Memo on Constructing a Hydraulic Barrier to Prevent Vertical Groundwater Migration

The findings presented in the Stantec memo concerning the ability to construct a hydraulic barrier within the pit backfill, and to seal the excavation damage zone behind the pit wall, are sound. My experience indicates hydraulic barriers constructed using state-of-the-practice construction techniques, appropriate materials and rigorous quality control / quality assurance procedures, typically achieve hydraulic conductivity values in the range from 10^{-8} to 10^{-7} cm/s. I support Stantec's conclusion that an effective vertical hydraulic conductivity of 10^{-8} cm/s is at the lower end of demonstrated technology. Increasing the thickness of a hydraulic barrier will delay the arrival of the wetting front at the contact with the Dakota Sandstone but would not prevent the eventual upward movement of groundwater into the Dakota Sandstone. Note that backfill placed below the barrier would need to retain sufficient hydraulic conductivity to transmit the regional flow component in the Jackpile Sandstone.

Localized cracking of a horizontal barrier, due to differential settlement of backfill material placed between the current pit floor and the base of the hydraulic barrier, is a risk to barrier performance that cannot be discounted, even with a high standard of construction. This cracking could markedly increase the effective hydraulic conductivity of the barrier layer. Furthermore, it could take several decades after backfilling for the effects of differential settlement to be expressed, so it would not be possible in the near term to confirm the numeric value of hydraulic conductivity of a constructed barrier which controls the long-term hydraulic behavior of the backfill.

Sealing an extensive damage zone in the upper Jackpile Sandstone around the pit wall using grout techniques will not be able to reasonably achieve a hydraulic conductivity that is sufficiently low to prevent upward seepage through the damage zone. Further, the scope of such an effort would be immense, with worker safety a paramount concern. I support Stantec's view that reducing the hydraulic conductivity in fractured rock to about 10^{-6} cm/s is a common circumstance, when following a well-executed grouting program. Values of hydraulic conductivity orders of magnitude lower than this do not seem achievable, and confirmation of seal performance likely not feasible in this setting.

Geomembrane liner installation on the pit walls would require considerable effort to develop a suitable bedding layer for liner placement and to form a secure seal to the wall, all in a challenging work environment. With respect to using a geomembrane liner to form a horizontal barrier within the backfill material, I concur with Stantec's discussion of liner leakage characteristics.

Setting aside the lack of precedent in constructing such low permeability barriers using mine waste materials, a final important issue, in my view, concerns the difficulties associated with confirming that hydraulic conductivities of the in-pit barrier and the excavation damage zone at or below demonstrated values have been achieved. The residual uncertainty in declaring that design values to prevent seepage have been achieved is likely to be uncomfortably large.