APPENDIX D

Technical Memorandum 4

Technical Memorandum 4

To: Montana Department of Environmental Quality

From: Environmental Resources Management

Date: December 21, 2017

Subject: Black Butte Copper Project - Tunnel and Shaft Plugs for Controlling Groundwater Flow at Closure

BACKGROUND

The Mine Operating Permit (MOP) for the Black Butte Copper Project (the Project) indicates that during operations, production workings would be continuously backfilled with low-permeability cemented tailings, but access tunnels and ventilation shafts would not be backfilled. During closure, cement plugs would be placed at strategic locations in the decline and access ramps, but these openings would otherwise not be backfilled. A subsurface plug would be placed in each of the four ventilation shafts, and portions of the shafts would be backfilled with non-cemented reclamation fill. The non-cemented fill would have relatively high hydraulic conductivity and not provide a water seal. Except where plugs are placed, this memorandum treats the decline, access ramps, and all ventilation shafts as hydraulically "open."

Baseline data indicate the general presence of upward hydraulic gradients, which would provide the potential for upward groundwater flow after the hydrologic system recovers from the hydraulic stresses imposed by the dewatering operation. Upward flow, if not controlled, could cause mine-impacted groundwater in deeper geologic units to migrate upward and affect the water quality in shallower units, most notably the Lower Newland A Formation (Ynl-A) unit and alluvial units that discharge groundwater into streams. In the natural hydrogeologic system, upward migration is very slow because the geologic units generally have low vertical hydraulic conductivity. However, the presence of (hydraulically) open tunnels and shafts could provide conduits that convey upward flow in a way that by-passes the containment afforded by the natural undisturbed system. Thus, the sealing provided by plugs in otherwise open tunnels and shafts is an important closure issue for the Environmental Impact Statement (EIS).

CURRENT MOP

As discussed in the MOP, the Proponent proposes to install 14 cement plugs at strategic locations in the main decline, deeper access ramps, and four ventilation shafts to restrict upward groundwater flow after closure and prevent human access. The locations of the plugs are shown on MOP Figures 7.4 and 7.5. The purpose of the plugs is to provide the following hydraulic separations:

- Between the Volcano Valley Fault (VVF) and overlying geologic units
- Between the lower and upper mine stopes of the Lower Sulfide Zone (LSZ)

- Between the Lower Copper Zone (LCS) and Lower Newland B Formation (Ynl-B)
- Between the Upper Sulfide Zone (USZ)/Upper Copper Zone (UCZ) and the Ynl-A

A plug would be installed at the water table in the main decline. Five additional plugs would be installed where the decline and all four ventilation shafts intersect ground surface to prevent physical access and invasion of surface water.

CONSTRUCTION ISSUES

The plugs would be installed at the end of mining with the dewatering system still operating to maintain dry excavations. After plug installation, the dewatering system would be turned off (or operated at systematically decreasing flow rates) to allow the mine to flood with groundwater. The engineering design will assess and recommend the construction of plugs that have low hydraulic conductivity to provide adequate sealing and sufficient strength to remain stable when subjected to differential water pressures on opposite sides of the plugs. Construction options include cement-only plugs or cement layered with foam. It is reasonable to assume that the plug material would have an effective hydraulic conductivity less than or equal to 10^{-7} centimeters per second (cm/sec) (0.00028 feet per day [ft/day]).

Two important construction issues are (1) development of cracks in the plug material after placement and (2) incomplete sealing at the cement/rock interface. Historically, both problems have occurred in tunnel/shaft seals but are generally attributed to improper cement mixes or inadequate methods of cement placement. With good quality engineering and modern construction practices, it is expected that these problems could be prevented or minimized.

A less tangible issue is the development of a disturbed zone adjacent to the tunnel or shaft wall due to blasting when the rock is first excavated. The blasting process could create fractures that extend outward from the rock face, and stress release can cause these (and natural) fractures to open. The result could be a zone adjacent to the wall with hydraulic conductivity that is greater than the undisturbed rock further away from the wall. It is considered that the thickness of the disturbed zone could range from 4 to 12 feet; for analyses in this memorandum, a thickness of 8 feet is assumed. The poor sealing performance of some tunnel plugs has been attributed to by-pass in the disturbed zone adjacent to the plug. The MOP states that if a detrimental disturbed zone is suspected, a fracture-grouting program will be initiated to seal fractures prior to plug placement. To do this, boreholes would be drilled outward from the rock face and grout would be injected into fractures under pressure. Experience has shown this technique to have mixed success in reducing groundwater flows below dams or into underground tunnels.

EIS ENVIRONMENTAL ISSUES

An important EIS environmental issue revolves around the function of plugs to reduce upward flow and chemical migration of potentially impacted water from deeper to shallower geologic units. Compared to deeper bedrock units, the Ynl-A has higher hydraulic conductivity and could be used for the development of low-capacity water wells. Groundwater in the Ynl-A unit also tends to discharge into streams, either directly or via alluvium adjacent to the streams. There is concern that open tunnels and shafts extending downward for many hundreds of feet could provide conduits that convey chemically affected water upward at flow rates that are higher than the natural system and with reduced travel times. At a scoping level, this technical memorandum attempts to address the utility of plugs in reducing enhanced upward flow that could otherwise occur in open tunnels and ventilation shafts.

TECHNICAL APPROACH

This memorandum provides a scoping-level evaluation of plug performance using (1) historical documentation, (2) details of the plugging program presented in the MOP, and (3) analytical calculations. It is not meant to be a definitive evaluation of the plug issue; this memorandum is meant to provide evidence on the expected success of plug installation at the Project mine and the ability of plugs to reduce the upward flow and migration of potentially affected mine waters.

USE OF TUNNEL AND SHAFT PLUGS IN MINING

Many mining operations, particularly those in mountainous terrain, rely on tunnel plugs to permanently seal mine adits and to flood (at least in part) the mine workings upon closure. It is generally accepted that the design criteria for permanent mine closure plugs should be stricter than those used during mine operations, particularly if the plug is used to impound acid rock drainage. In most cases, it is the allowable seepage/gradient rather than the shear strength of the rock or concrete that controls the length of the plug (Lang 1999).

The Natural Resources Conservation Service Conservation Practice Standard for Mine Shaft and Adit Closing (Code 457) enumerates the closing of underground mine excavations by filling, plugging, capping, and installing barriers with the following objectives:

- Reduce hazards to humans and/or animals.
- Maintain or improve access and/or habitat for wildlife.
- Protect cultural resources.
- Reduce subsidence problems.
- Reduce the emission of hazardous gases.
- Reduce or prevent contamination of surface water and groundwater.

Kirjapaino Oy (2008) writes that, in addition to reducing subsidence risk, the use of adit plugs can prevent the physical migration of the mine backfill if it becomes saturated with water. Installation of plugs and rock fill is not generally recommended in access tunnels and shafts in case the mine is to reopen at some future date.

Among the plug purposes enumerated on Code 457, two appear to be applicable to the proposed Project upon its future closure: (1) reduce hazards to humans and/or animals; and (2) reduce or prevent contamination of surface water and groundwater.

PLUGGING PROGRAM PRESENTED IN THE MOP

MOP Figures 7.4 and 7.5 show the proposed locations of plugs. ERM's review of the MOP identified the following plug issues that merit additional consideration in the EIS:

- As shown on Figure 7.5, the lower portion of the lower intake ventilation shaft (IVL) is continuously open and connects to the lower decline. The lack of a plug in the lower IVL may negate the hydraulic function of the decline plugs labeled "Upper VVF" and "Below USZ" on Figures 7.4 and 7.5.
- As shown on Figure 7.5, the lower portion of the lower exhaust ventilation shaft (EVL) has no plugs, but connects the middle decline to a lower access ramp. The lack of a plug in this portion of the EVL may negate the hydraulic function of the plug labeled "Upper VVF" on Figure 7.5.
- It is not entirely clear in the MOP which portions of the ventilation shafts would be backfilled.
- The MOP indicates that a plug would be installed at the groundwater table in the decline, but the hydraulic utility of a plug at this location is unclear.

HYDRAULIC ANALYSIS OF PLUG PERFORMANCE

Figure A-1 in Appendix A of this memorandum shows conceptual flow paths for leakage that could occur through and past a tunnel plug. While the plug itself is generally of low permeability and entails minimal flow, significant leakage could occur in the disturbed zone adjacent to the tunnel wall that likely would have higher hydraulic conductivity than the undisturbed rock mass. In this section, scoping-level calculations are performed to evaluate leakage through the plug and in the disturbed zone. Flow in the undisturbed rock mass is not considered because it is expected to be relatively small. However, if the rock mass has appreciable hydraulic conductivity, this flow component might be significant and could be evaluated using numerical methods.

Flow By-Passing a Tunnel or Shaft Plug

The hydraulic performance of a tunnel plug at the Project site was evaluated based on the conceptualization shown on Figure A-2. The plug being considered is for the EVL raise and would be used to hydraulically separate the USZ/UCZ unit from the overlying Ynl-A unit. This location is of interest because the Ynl-A has relatively high hydraulic conductivity and there are nearby piezometers that provide reliable data on the vertical hydraulic gradient (MW-9, PW-9, and PW-10). The hydraulics of a shaft at this location without a plug was independently analyzed in the MOP (Section 4.1.7.2) and summarized on MOP Figure 4.15. At the EVL location, the static hydraulic head in the USZ/UCZ unit is higher than the head in the Ynl-A unit, providing the potential for upward flow, which would be enhanced by the presence of an open shaft. The intended purpose of the plug would be to reduce the upward flow between the two units.

The conceptualization on Figure A-2 considers radial horizontal flow converging into the shaft from the underlying USZ/UCZ unit, flow up the shaft with or without a plug, and radial flow away from the shaft into overlying Ynl-A unit. The system flow rate is affected by flow through a disturbed zone adjacent to the shaft wall that has higher hydraulic conductivity than the undisturbed rock mass. For this evaluation, the disturbed zone is assumed to be 8 feet thick and have a possible hydraulic conductivity (K_d) ranging from 0.1 ft/day (slightly less than undisturbed USZ/UCZ rock) to 100 ft/day for highly disturbed rock.

The following steady-state equation (Theim 1906; Kruseman and de Ridder 1990) is used to compute horizontal radial flow into the shaft from the USZ/UCZ unit (Q_2):

$$Q_2 = \frac{2\,\pi\,K_{h2}\,b_2\,(H_2 - H_{s2})}{F}$$

where:

K_{h2} = horizontal hydraulic conductivity of geologic materials in USZ/UCZ (0.16 ft/day)

b_2 = effective thickness of more permeable geologic materials within USZ/UCZ (46 feet)

H_2 = static hydraulic head in the USZ/UCZ unit (5,703.4 feet mean sea level [msl])

H_{s2} = Hydraulic head in the shaft below the plug (computed)

F = steady-state shape factor (5.7)

Steady-state flow from the shaft into the Ynl-A (Q_1) is computed similarly:

$$Q_1 = \frac{2\,\pi\,K_{h1}\,b_1\,(H_{s1} - H_1)}{F}$$

where:

K_{h1} = horizontal hydraulic conductivity of geologic materials in Ynl-A (1.3 ft/day)

b_1 = effective thickness of more permeable geologic materials within Ynl-A (46 feet)

H_1 = static hydraulic head in the Ynl-A unit (5,696.1 feet msl)

H_{s1} = hydraulic head in shaft above the plug (computed)

The steady-state shape factor (F) for horizontal radial flow is typically given by:

$$F = ln\left(\frac{r_w}{r_o}\right)$$

where:

r_w = well radius (in this case the shaft radius)

r_o = radius of influence; distance to where the hydraulic head is near static

The typical value used for practical application is F = 5.7, which implies that the ratio (r_w/r_o) is equal to 300.

The combined vertical flow through the plug and disturbed zone (Q_3) is computed using the Darcy equation:

$$Q_3 = \left(K_p\,A_p + K_d\,A_d\right)\left(\frac{H_{s2} - H_{s1}}{L}\right)$$

where the cross-sectional area of the plug (A_p) is:

$$A_p = \frac{\pi}{4} D^2$$

the cross-sectional area of the disturbed zone (A_d) is:

$$A_d = \frac{\pi}{4} [(D + 2\, a)^2 - D^2]$$

and:

D = shaft diameter (16 feet)
a = thickness of disturbed zone (8 feet)
L = plug length (20 feet)
K_p = hydraulic conductivity of plug material (0.0003 ft/day = 10^{-7} cm/sec))
K_d = hydraulic conductivity of disturbed zone (range of 0.1 ft/day to 100 ft/day)

and other parameters are previously defined.

In the direction of flow, continuity requires that:

$$Q_2 = Q_3 = Q_1$$

Starting with the known static head in USZ/UCZ (H_2), algebraic manipulation of the above equations is used to *compute* a static head in Ynl-A. Then by an iterative process, the system flow rate (Q) is modified until this computed head is equal to the known static head in Ynl-A (H_1). The computations are programmed in the Mathcad worksheet provided in Figure A-3. As a sensitivity analysis, the flow rate (Q) was computed for different values of the disturbed zone hydraulic conductivity (K_d) to evaluate how the plug would perform with different amounts of by-pass leakage in the disturbed zone adjacent to the plug.

Calculations show that if the hydraulic conductivity of the plug material (cement and/or foam) is less than 0.003 ft/day (10^{-6} cm/sec), the flow through the plug can be neglected. However, the system flow rate is affected by the disturbed zone hydraulic conductivity (K_d). To evaluate how the plug might perform, a series of calculations were performed using K_d values ranging from 0.1 ft/day (slightly less than the undisturbed USZ/UCZ hydraulic conductivity of 0.16 ft/day) to a very high value of 100 ft/day. The inputs listed in Figure A-3 are for one realization where the disturbed zone hydraulic conductivity is taken to be 1.6 ft/day, or one order-of-magnitude greater than that of undisturbed USZ/UCZ rock. Other realizations use the same inputs except for the disturbed zone hydraulic conductivity (K_d).

Results of the analysis are shown graphically on Figure A-4. As the disturbed zone hydraulic conductivity (K_d) increases, the upward vertical flow by-passing the plug also increases, which makes logical sense. However, it is surprising that for a three order-of-magnitude increase in K_d, the by-pass flow rate only increases by a factor of three (from 0.08 gallon per minute [gpm] to 0.27 gpm). This is because the effect of higher K_d on flow is counteracted by a reduction in the hydraulic gradient through the disturbed zone. Note that for the K_d values greater than 10 ft/day, the by-pass flow rate is similar to the value computed in the MOP for the case of no plug (0.27 gpm). As K_d increases, the hydraulic head in the shaft below the plug (H_{s2}) becomes more similar to the head above the plug (H_{s1}). For K_d greater than 10 ft/day, the heads are nearly equalized and similar to the value of 5,697 feet msl computed in the MOP for the no-plug case. This analysis suggests that shaft plugs can reduce groundwater flow through a shaft or tunnel; however, for the rock properties considered in this example, the flow reduction (0.27 gpm to 0.08 gpm) is not very large.

At face value, one might interpret from Figure A-4 that the system flow rate can be greatly reduced by grouting fractures in the disturbed zone so that K_d is a very low value. However, the effect of this would be to shift the flow lines to outside the disturbed zone away from the shaft, so the reduction in flow rate may not be as great as envisioned. To properly analyze this type of situation would likely require an axisymmetric numerical flow model, which while doable, was outside the scope of this technical memorandum.

Assuming an effective porosity of 0.10, Figure A-5 shows the migration velocity and sharp-front travel time for unattenuated chemical migration through the disturbed zone. For K_d increasing from 0.1 ft/day to 100 ft/day, the sharp-front travel time decreases from about 77 days to 23 days, which is not a large change.

Natural Vertical Flow

Figure A-6 considers natural vertical groundwater flow in the same geologic units considered for the shaft analysis. Based on calibration of the site groundwater model, the vertical hydraulic conductivity of USZ/UCS unit is taken to be 0.011 ft/day and the vertical hydraulic conductivity of Ynl-A is 0.26 ft/day. The static hydraulic head in USZ/UCZ at PW-9 is 5,703.4 feet msl and the head in Ynl-A at MW-9 is 5,696.1 feet msl. Based on well completion data, the vertical distance between midpoints of the completion intervals for these wells is 110 feet. Because the vertical hydraulic conductivity of the USZ/UCZ unit is lower than that of the overlying Ynl-A, the vertical hydraulic gradient in the USZ/UCZ unit should be greater as shown by the conceptual head distribution graph on Figure A-6. For a given vertical flow rate, the Mathcad worksheet in Figure A-7 computes the map area associated with natural vertical flow for that flow rate. Figure A-7 considers a vertical flow rate of 0.27 gpm, which is the estimated flow rate for the shaft without a plug. The equivalent area of natural vertical flow for this flow rate is computed to be 1.24 acres. Thus, the vertical leakage for a shaft without a plug is equivalent to the natural vertical flow that takes place over a footprint area of 1.24 acres. For the case of a plug with a lower permeability disturbed zone, the estimated shaft leakage is estimated to be about 0.1 gpm, and this is equivalent to a natural flow area of about 0.5 acre. The implication here is that the total upward flow through four vent raises and one decline, with or without plugs, would be relatively small compared to the upward natural flow that occurs over the general area of the mine.

Vertical seepage velocity and travel time in the natural system is also assessed in the Mathcad worksheet. For an effective porosity of 0.10, the vertical seepage velocity is 3.5 feet per year (ft/yr). For the vertical distance of 110 feet between the mid-points of PW-9 and MW-9, the computed sharp-front travel time is on the order of 30 years. Calculations confirm that this travel time is independent of the flow rate considered in Figure A-7.

Discussion

This analysis provides evidence supporting the following statements:

- After closure and hydraulic recovery, the presence of four shafts and one decline, with or without plugs, would not substantially change the natural upward flow that would occur between lower geologic units and the Ynl-A unit. With or without plugs, the upward flow rate through the openings would be small compared to natural upward flow that would occur in areas where there are no mine openings.
- The placement of shaft and tunnel plugs just below the USZ/UCZ – Ynl-A contact would reduce flow in the openings, but the relative decrease would not be very large.
- The greatest effect of shafts and tunnels is reducing the chemical migration times from deeper units into the Ynl-A unit. In areas without openings, the travel time for upward flow in geologic materials would likely be many decades to perhaps centuries. However, where shafts and tunnels would be installed, the upward travel time, with or without plugs, could be less than several years.
- If an environmental priority is to increase the time it takes for chemicals in deeper units to reach the Ynl-A unit, the only practical engineering approach would be to completely backfill the shafts and declines with a granular porous material so that upward (Darcian) flow could occur in a medium with reasonably high effective porosity (which reduces migration velocity). If the backfill were to have low hydraulic conductivity (such as cemented tailings), this approach could eliminate the need for all subsurface plugs.

CONCLUSIONS AND RECOMMENDATIONS

The main conclusion of this technical evaluation is that the upward migration of potentially affected groundwater into shallower geologic units via shafts and tunnels would be relatively rapid regardless of whether or not plugs are installed. Mixing calculations might show that the flow rates are small enough to not significantly impact the Ynl-A water quality, but the time frame for chemicals to migrate up the tunnels and shafts is relatively rapid. Calculations show that placement of plugs would not greatly increase the travel times compared to shafts and tunnels that do not have plugs. If minimizing upward vertical chemical migration from deeper to shallower units is an EIS priority, the only engineering solution may be to completely backfill the decline, access ramps, and ventilation shafts with non-cemented or cemented granular material. It is recommended that this be established as an alternative in the EIS. The alternative might entail stockpiling an adequate volume of tailings or other granular material at the end of mining, which could be used to backfill all tunnels and shafts prior to turn-off of the dewatering system. If tailings are used for backfill, one consequence of this approach would be a smaller ultimate volume of tailings to be placed in the cemented tailings facility (CTF). Engineering options can consider the use of non-cemented or cemented backfill material.

For the closure approach currently described in the MOP, other EIS alternatives may consider the following:

- One additional plug in the lower portion of the IVL to hydraulically separate the VVF from shallower geologic units.
- One additional plug in the lower portion of the EVL to hydraulically separate the VVF from shallower geologic units.
- Elimination of the water-table plug in the decline (labeled “At GWT” on MOP Figures 7.4 and 7.5).

REFERENCES

Kirjapaino Oy, V. 2008. Mine Closure Handbook - Environmental Techniques for the Extractive Industries (Vammalan Kirjapaino Oy). ISBN 978-952-217-042-2.

Kruseman, G.P and N.A. de Ridder. 1990. “Analysis and Evaluation of Pumping Test Data.” International Institute for Land Reclamation and Improvement, Publication 47, Wageningen, Netherlands.

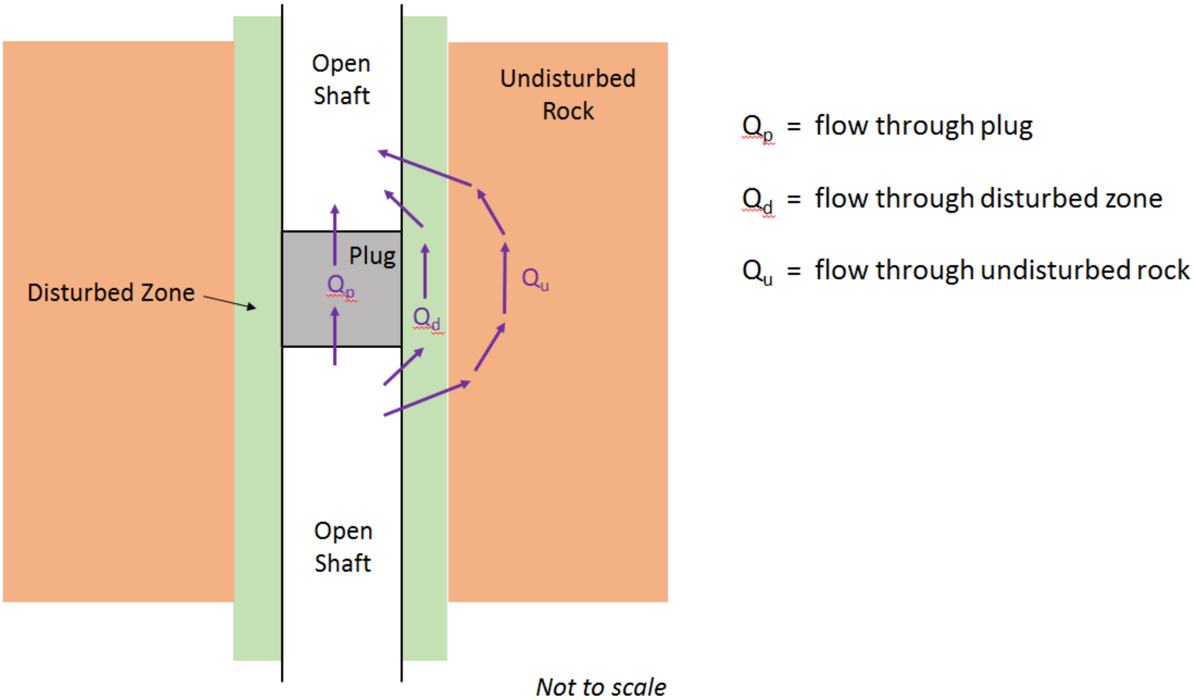
Lang, B. 1999. “Permanent Sealing of Tunnels to Retain Tailings or Acid Rock Drainage.” In Proceedings of the Mine, Water & Environment - IMWA Congress, Sevilla, Spain.

Natural Resources Conservation Service Conservation Practice Standard for Mine Shaft and Adit Closing (No.) Code 457.

Theim, G. 1906. Hydrologische Methoden. Gebhardt, Leipzig, Germany.

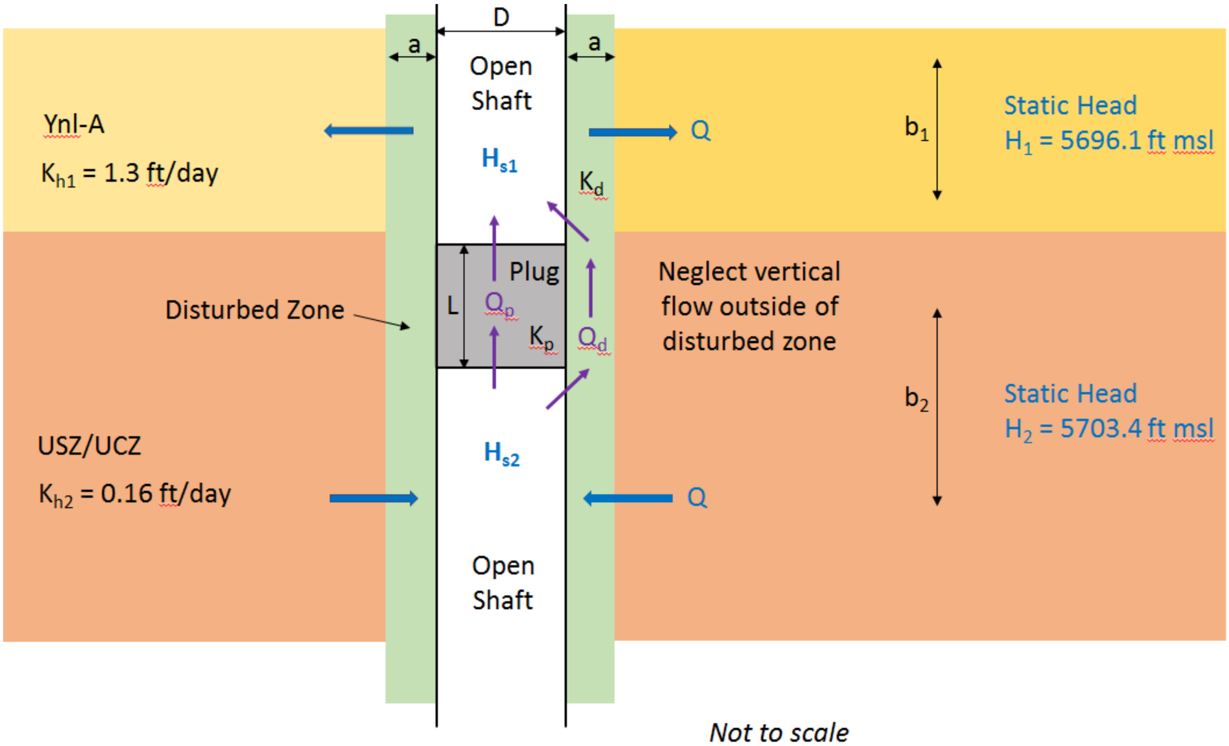
Technical Memorandum 4: Appendix A

Figure A-1: Flow Patterns Through and Around a Plug



Not to scale

Figure A-2: Flow Analytical Model



Not to scale

Figure A-3: Flow Through (and By-passing) a Plug

Inputs

$H_1 := 5696.1 \cdot ft$	Static hydraulic head in Ynl-A unit	
$K_{h1} := 1.3 \cdot \frac{ft}{day}$	Horizontal hydraulic conductivity of Ynl-A unit	
$b_1 := 46 \cdot ft$	Permeable thickness of Ynl-A unit	
$H_2 := 5703.4 \cdot ft$	Static hydraulic head in USZ unit	
$K_{h2} := 0.16 \cdot \frac{ft}{day}$	Horizontal hydraulic conductivity of USZ unit	
$b_2 := 46 \cdot ft$	Permeable thickness of USZ unit	
$L := 20 \cdot ft$	Length of plug	
$D := 16 \cdot ft$	Shaft diameter	
$a := 8 \cdot ft$	Thickness of disturbed zone	
$K_d := 1.6 \cdot \frac{ft}{day}$	Hydraulic conductivity of disturbed zone	
$F := 5.7$	Shape factor for radial flow to shaft	
$K_p := 0.000284 \cdot \frac{ft}{day}$	Hydraulic conductivity of plug	$K_p = 1.00 \times 10^{-7} \cdot \frac{cm}{sec}$
$\phi := 0.10$	Effective porosity of disturbed zone	

Calculations

$A_d := \frac{\pi}{4} \cdot \left[(D + 2 \cdot a)^2 - D^2\right]$	Cross-sectonal area of disturbed zone	$A_d = 603.186 \cdot ft^2$
$A_p := \frac{\pi}{4} D^2$	Cross-sectional area of plug	$A_p = 201.062 \cdot ft^2$
$H_{s2}(Q) := H_2 - \frac{Q \cdot F}{2 \cdot \pi \cdot K_{h2} \cdot b_2}$	Hydaulic head in shaft below plug	
$H_{s1}(Q) := H_{s2}(Q) - \frac{Q \cdot L}{K_d \cdot A_d + K_p \cdot A_p}$	Hydraulic head in shaft above plug	
$H(Q) := H_{s1}(Q) - \frac{Q \cdot F}{2 \cdot \pi \cdot K_{h1} \cdot b_1}$	Computed static head in Ynl-A	
$q := 0 \quad Q := \mathrm{root}(H(q) - H_1, q)$	Find by-pass flow rate for $H(Q) = H_1$	$Q = 0.2383 \cdot gpm$
	Computed head in shaft below plug	$H_{s2}(Q) = 5697.75 \cdot f$
	Computed head in shaft above plug	$H_{s1}(Q) = 5696.80 \cdot f$
$Q_p := K_p \cdot A_p \cdot \left(\frac{H_{s2}(Q) - H_{s1}(Q)}{L}\right)$	Computed flow rate through plug	$Q_p = 0.000 \cdot gpm$
$Q_d := K_d \cdot A_d \cdot \left(\frac{H_{s2}(Q) - H_{s1}(Q)}{L}\right)$	Computed flow rate through disturbed zone	$Q_d = 0.238 \cdot gpm$
$v_d := \frac{Q_d}{A_d \cdot \phi}$	Seepage velocity in disturbed zone	$v_d = 0.76 \cdot \frac{ft}{day}$
$t_d := \frac{L}{v_d}$	Sharp-front travel time through disturbed zone	$t_d = 26.302 \cdot day$

Figure A-4: Results of Shaft Plug Analysis

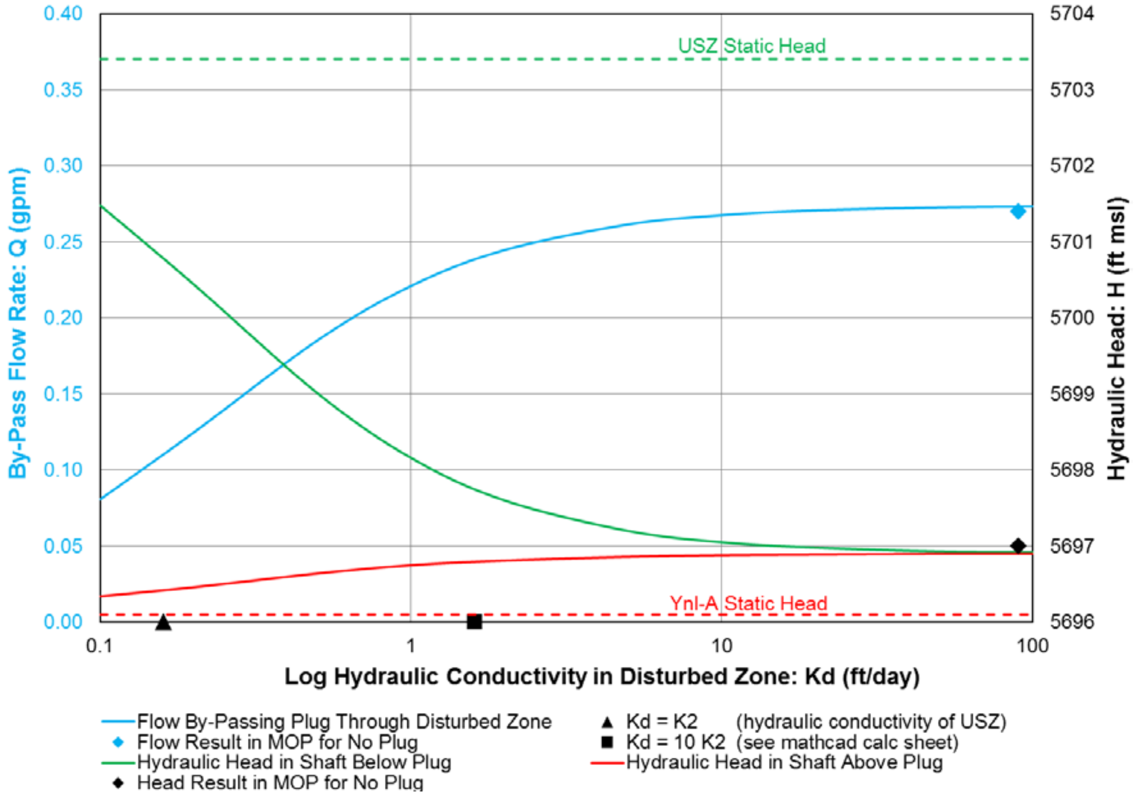


Figure A-5: Chemical Migration Past Plug

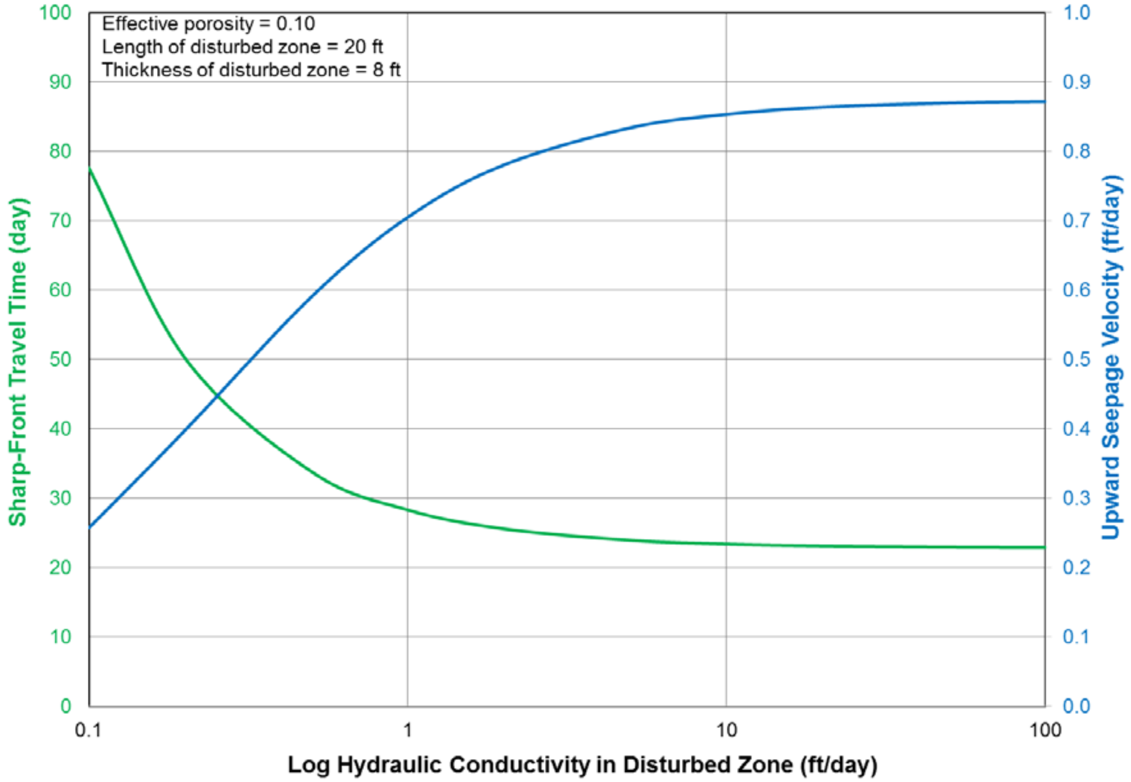
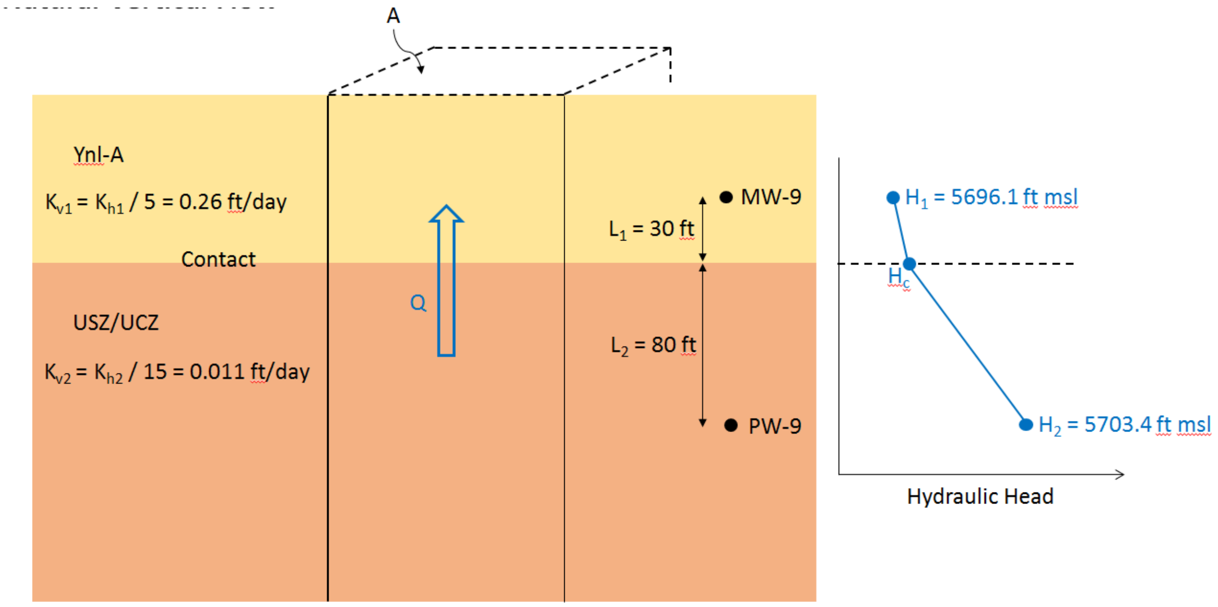


Figure A-6: Natural Vertical Flow



Not to scale

Figure A-7: Natural Vertical Flow (in Absence of Shaft)

Inputs

$H_1 := 5696.1\cdot\mathrm{ft}$	Static head in Ynl-A	
$K_{v1} := \frac{1.3}{5}\cdot\frac{\mathrm{ft}}{\mathrm{day}}$	Vertical hydraulic conductivity in Ynl-A based on numerical model calibration	$K_{v1} = 0.26\cdot\frac{\mathrm{ft}}{\mathrm{day}}$
$L_1 := 30\cdot\mathrm{ft}$	Vertical distance from midpoint of MW-9 completion to the Ynl-A / USZ contact	
$H_2 := 5703.4\cdot\mathrm{ft}$	Static head in USZ (PW-9)	
$K_{v2} := \frac{0.16}{15}\cdot\frac{\mathrm{ft}}{\mathrm{day}}$	Vertical hydraulic conductivity in USZ based on numerical model calibration	$K_{v2} = 0.011\cdot\frac{\mathrm{ft}}{\mathrm{day}}$
$L_2 := 80\cdot\mathrm{ft}$	Vertical distance from Ynl-A / USZ contact to midpoint of MW-9 completion	
$Q := 0.27\cdot\mathrm{gpm}$	Vertical flow rate considered	
$\phi := 0.10$	Effective porosity of undisturbed rock	

Calculations

$H_c(A) := H_2 - \frac{Q\cdot L_2}{K_{v2}\cdot A}$	Hydraulic head at Ynl-A / USZ contact	
$H(A) := H_c(A) - \frac{Q\cdot L_1}{K_{v1}\cdot A}$	Computed static head Ynl-A (MW-9)	
$a := 0.5\cdot\mathrm{acre} \quad A := \mathrm{root}(H(a) - H_1, a)$	Find map area for which computed head in Ynl-A equals H_1 when vertical flow rate is Q	$A = 1.24\cdot\mathrm{acre}$
	Actual head head in Ynl-A (MW-9)	$H_1 = 5696.1\cdot\mathrm{ft}$
	Computed head in Ynl-A (MW-9)	$H(A) = 5696.1\cdot\mathrm{ft}$
	Conputed head at Ynl-A / USZ contact	$H_c(A) = 5696.2\cdot\mathrm{ft}$
	Head in USZ (PW-9)	$H_2 = 5703.4\cdot\mathrm{ft}$
$i_1 := \frac{H_1 - H_c(A)}{L_1}$	Vertical hydraulic gradient in Ynl-A (negative for upward flow)	$i_1 = -0.004$
$i_2 := \frac{H_c(A) - H_2}{L_2}$	Vertical hydraulic gradient in USZ (negative for upward flow)	$i_2 = -0.090$
$v := \frac{Q}{A\cdot\phi}$	Vertical seepage velocity	$v = 3.50\cdot\frac{\mathrm{ft}}{\mathrm{yr}}$
$t := \frac{L_1 + L_2}{v}$	Sharp-front travel time over 110 vertical feet from PW-9 to MW-9	$t = 31.4\cdot\mathrm{yr}$