ABANDONED UNDERGROUND MINE REMEDY EVALUATION AND REMEDIAL DESIGN CAPTAIN JACK MILL SUPERFUND SITE, COLORADO

A.S. Bazin, P.E.

AMEC Environment & Infrastructure, Inc.
2000 S. Colorado Blvd, Suite 2-1000
Denver, CO 80222

ABSTRACT

This paper is focused on the methods and objectives of the pre-design investigation and the elements of the design used to provide a long-term, low-maintenance remedy under difficult site conditions at a remote, mountainous site. The paper describes the use of advanced geophysical methods such as surface and downhole electrical resistivity tomography, solar powered monitoring systems, and remote data acquisition and communications. The paper will also discuss the comparative benefits and disadvantages of the active and passive treatment systems evaluated, including a limestone bed, caustic injection, and a sulfate-reducing bioreactor. Remedy design is nearly complete and installation is tentatively slated for the summer of 2014.

Key Words: bulkhead, passive treatment, remote monitoring, ERT

INTRODUCTION

The Captain Jack Mill (CJM) Superfund Site (the Site) is a former gold and silver mine located in Boulder County, Colorado. AMEC is responsible for the pre-design investigations and design of the subsurface remedy. The remedy must be designed to meet the description of the selected remedy in the Record of Decision (ROD), which includes:

- Construction of a bulkhead to plug the Big Five Tunnel and stop the flow of acidic mine drainage and loading of heavy metals to Left Hand Creek;
- In-situ treatment of the resultant flooded mine workings;
- Long-term monitoring of the mine pool and surrounding surface and subsurface hydrogeologic changes.

In order to meet these requirements, the remedial approach includes a concrete, flow-through bulkhead to seal the portal and flood the underground mine workings to limit the formation of acid mine drainage (AMD). Other aspects of the remedial design include passive limestone treatment, mine pool recirculation with injection of a caustic, and innovative long-term monitoring techniques.

In order to develop the remedial design, AMEC conducted an intensive pre-design investigation that included advanced geophysical methods, drilling, tracer studies, and water quality monitoring. AMEC evaluated several treatment alternatives, which are also discussed. The selected remedy is designed to provide a long-term, low-maintenance remedy under difficult site conditions at a remote, mountainous site. System installation is tentatively slated for the summer of 2014.

SITE DESCRIPTION

The Site is located in a remote part of Boulder County, Colorado at an elevation of approximately 8,800 feet amsl. Given the steep, mountainous terrain and snowy winters, the site is only accessible from late spring through early fall. As shown in Figure 1, the underground workings consist of a network of historic tunnels that collect groundwater and generate AMD.

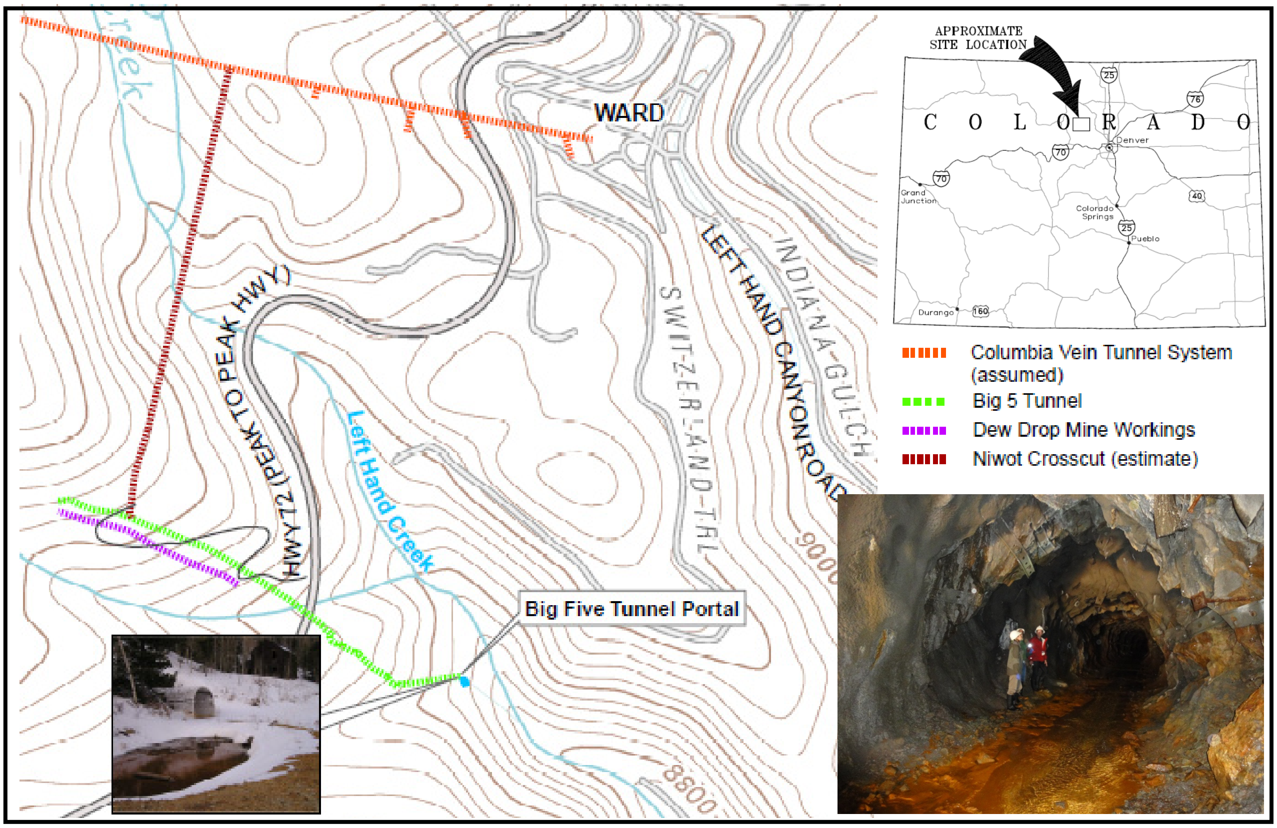

Figure 1 - Captain Jack Mine Workings

The extent of the mine workings that contribute to AMD include three major tunnel systems - the Big Five Tunnel, the Dew Drop Tunnel, and the Niwot Crosscut. These tunnels contain miles of workings over multiple levels that connect to form a complex set of workings. The mine workings of primary importance are the Big Five Tunnel, where the bulkhead will be located.

The Big Five Tunnel extends northwest from the portal at a slope of approximately 1%. It was excavated horizontally for several thousand feet to access the Majestic Claim to the west. The portal of the Big Five Tunnel represents the low point of the workings, and drains at a seasonally fluctuating rate between 25 and 160 gpm. The water has a low pH (~3.0), contains dissolved heavy metals, and ultimately discharges to nearby surface waters. The Big Five Tunnel is approximately 9 feet in height by 10 feet wide, and is accessible for approximately 900 feet from the Portal, at which point a collapse limits further ingress. This 900-foot section underwent extensive rehabilitation in 2007, including the placement of new timbers, rock bolts, mesh, and shotcrete. Due to the collapse, the location of the tunnel beyond the collapse and the full extent of the mine workings are not known.

The Dew Drop Mine Tunnel runs approximately 250 feet above and parallel to the Big Five Tunnel, and is accessed at a portal west of the Peak to Peak Highway (Figure 1). Historical records note that a winze was constructed to connect the Dew Drop Tunnel to the Big Five Tunnel; however, miners familiar with the site have observed very little water entering the Big Five Tunnel from the Dew Drop winze. The exact location of the winze is not known.

The Niwot Crosscut connects the Big Five Tunnel to a larger network of workings to the North, called the Columbia Vein. The exact location of the Crosscut is unknown, but its length is estimated to be approximately 2,800 feet. The Columbia Vein includes many levels of workings, many of which are submerged. Adits and other entrances to the Columbia Vein workings are visible in the nearby town of Ward. It was initially believed that the slope of the Niwot Crosscut dipped towards Ward so that water from the mine pool would travel from the Big Five Tunnel into the Niwot Crosscut and on to the Columbia Vein workings. Further research has established that the Niwot Crosscut in fact drains from the Columbia mine workings south into the Big Five Tunnel. The Big Five Tunnel was used as a transportation corridor to bring ore from the Columbia Vein to a mill below the Big Five Tunnel and therefore would have been sloped to allow full mine carts to travel downhill.

Geology and Hydrogeology

The CJM Site is situated in an area that has been glaciated. Bedrock in the area is described as granite, granodiorite, and/or granitic gneiss. The fractured granite serves as an aquifer in the area. Water wells are commonly completed into the fractured granite. The Town of Ward is at roughly 9,200 feet msl while the Big Five Adit is approximately 8,800 feet msl. Groundwater in Ward is assumed to be upgradient based on this difference in surface elevation. Ward residents also receive domestic water from three separate springs located approximately 5 miles west of town, at a location up-gradient and outside of the 4-mile radius of the Site. Recharge to the surficial and bedrock aquifers is primarily from snowmelt and rainfall infiltration (Walsh, 2008).

PRE-DESIGN INVESTIGATION

Borehole Construction

AMEC installed nine borings during the pre-design investigation (Figure 2).

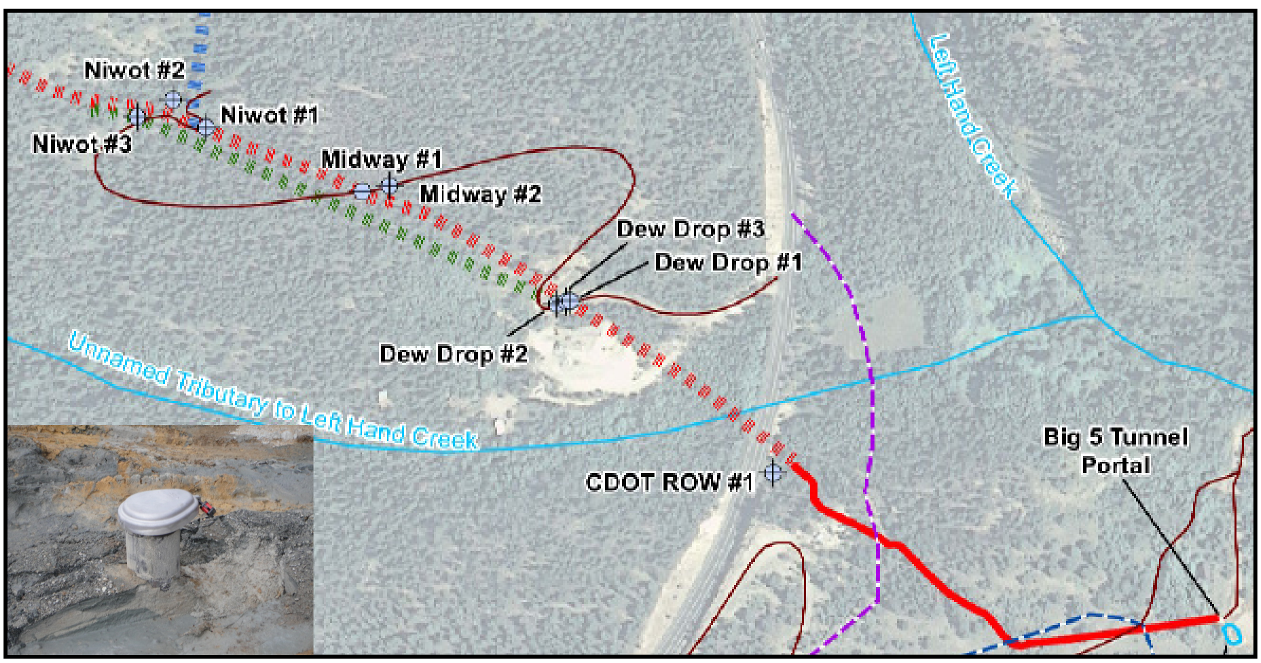

Figure 2 – Borehole Locations

The borings were used to characterize the hydrogeology, identify the extent of fracturing and fracture flow, study formation permeability, identify baseline groundwater chemistry, and obtain borehole geophysical data. These borings will be converted to monitoring wells or injection wells as part of the remedy. The following boreholes were constructed:

- **CDOT ROW #1**. Total boring depth is approximately 280 feet below ground surface (bgs).
- **Dew Drop #1**. Total boring depth is approximately 350 feet bgs.
- **Dew Drop #2.** Total boring depth is approximately 350 feet bgs.
- **Dew Drop #3.** Penetrates Big Five Tunnel; total boring depth is approximately 296 feet bgs to the roof of mine workings.
- **Midway #1.** Total boring depth is approximately 480 feet bgs
- **Midway #2**. Total boring depth is approximately 413 feet bgs.
- **Niwot #1.** A large, unidentified void space was encountered at approximately 365 feet bgs.
- **Niwot #2**. Encounters mine workings at 411 feet below top of casing (BTOC). These workings are believed to be an upper level of the Big Five Tunnel. No water was observed.
- **Niwot #3.** Shallow mine workings were encountered at approximately 146 feet BTOC and at 170 feet BTOC. The lower workings are believed to be a part of the Dew Drop Tunnel located adjacent to and shallower than the Big Five Tunnel. No water was observed.

Surface Resistivity

Zonge International, Inc. completed surface geophysical surveys to help delineate the location and alignment of the Big Five Tunnel and other mine workings. The methods included dipole-dipole/ZETA electrical resistivity and induced polarization, as well as in-tunnel Mise-a-la-masse (MALM) resistivity surveys. During the survey an electrode was placed into the Big Five Tunnel water flow at the collapse and dipole-dipole/ZETA data and MALM were acquired. In one MALM survey, an electrode in the Dew Drop #3 boring was used in addition to the Big Five Tunnel transmitting electrode.

Processing and interpretation of the MALM data confirmed that the historical renderings of the tunnel locations appear to be fairly close to the geophysical field observations. Using the tunnel flow as a transmitting electrode, it appears the MALM surveys were able to image its approximate position up to the Niwot intersection, significantly narrowing the location of that feature. Westward beyond the intersection, it was very difficult to determine the connectedness of railings or other infrastructure in the mine. Loss of resolution due to the depths of the tunnels, and poor coupling to the mineralized mine wall or water-covered floor may contribute to the lack of response on the western and northern extremes of the survey area.

Electrical Resistivity Tomography (ERT)

Multi-Phase Technologies, LLC (MPT) conducted ERT surveys to help identify the tunnel location with respect to the Dew Drop #1 and Dew Drop #2 borings – both of which failed to intercept the tunnel. Both borehole-to-borehole surveys and surface-to-borehole surveys were completed. The ERT survey identified a low-resistivity area between the boreholes at a depth of approximately 290 feet, enabling AMEC to successfully intercept the tunnel with boring Dew Drop #3.

MPT also completed an ERT survey on the CDOT ROW #1, to determine if the Big Five Tunnel could be detected using borehole to surface geophysical methods. Two types of surveys were run, a borehole-to-surface array and a MALM array. MPT was capable of locating the tunnel depth, but the horizontal distance from the borehole to the tunnel could not be determined with accuracy. The borehole-to-borehole data and MALM to borehole/borehole data were found to give the most accurate information regarding the location of the tunnel.

Preliminary ERT evaluations indicate that seasonal and long-term groundwater changes may be determined using ERT. Once an initial background model is developed, subsequent data sets can be compared against the background. The surveys produce percent difference models that will show increases in conductivity and resistivity, thereby providing information on groundwater changes.

Borehole Surveys

RAS, Inc. conducted geophysical downhole logging of six of the Site borings, and formation pressure testing using inflatable packers on one boring. The purpose of this work was to evaluate the geophysical and hydrogeological characteristics of the crystalline rock in the vicinity of the Big Five Tunnel. The geophysical methods applied in each well are included in the table below.

Logging Method	CDOT ROW #1	Dew Drop #1	Dew Drop #2	Niwot Crosscut	Dew Drop #3	Midway #1
Caliper	X	X	X	X	X	X
Natural Gamma	X	X	X	X	X	X
Induction Resistivity		X	X	X	X	X
Galvanic Resistivity	X					
Optical Televiewer	X				X	X
Acoustic Televiewer	X	X	X			
Deviation	X	X	X	X	X	X
Ambient Fluid Conductivity	X	X	X			
Analog Video	X	X	X	X	X	
Packer Pressure Testing	X				X	

Table 1 – Borehole Geophysical Method Summary

Caliper

A 3-arm caliper log was conducted to provide data on borehole diameter and competency prior to logging with other tools. Each boring was approximately 6¾ inches in diameter and was generally without significant variation. In the boreholes that were also logged with the acoustic televiewer or optical televiewer, significant variations in hole diameter correlated with intervals of open fractures as suggested by interpretation of televiewer logs.

Natural Gamma

While gamma logs do not measure lithology directly, in a granitic rock environment natural gamma may reflect changes in mafic mineral content or higher potassium content. The gamma logs were similar in response range (generally 200 to 600 API units) and compared to the known and reported geology from driller's logs for stratigraphic correlation. Significant variations in gamma may be due to presence of ore veins or other higher gamma producing minerals. The fracture intervals suggested by televiewer log analysis or caliper log demonstrated no unique or consistent gamma responses that could be used to suggest the presence of these zones.

Resistivity

An induction resistivity log was conducted in five of the borings. The induction resistivity generally varied between 20 to 150 ohm-m in each borehole. Intervals of low resistivity (high conductivity) were noted in several intervals in each boring; however, they were not associated with any identifiable feature from the driller's logs. Also, intervals of high resistivity (low conductivity) were noted, but could not be associated with any significant lithologic, or other geophysical feature. In general, in each boring the resistivity log did not appear to correlate with other measured parameters; particularly fractures as identifies during OTV log analysis.

A galvanic resistivity log (16-64 inch normal) was conducted in CDOT ROW #1. Galvanic resistivity measures formation resistivity and is influenced by resistivity of the formation water, amount of water present, and fracture structure. In general, the logs suggest a relatively high resistivity (low conductivity) over the entire interval. The lower fracture frequency in this well may support generally high resistivity, which is common in a massive granitic rock environment. However the lack of correlation between variations in resistivity and conductivity, and fracture location in all of the borings, suggest that the resistivity primarily reflected formation resistivity and did not appear to clearly identify water-bearing flow zones.

Televiewer

Optical televiewer logging was conducted to identify structure and assess fracture orientation and aperture. Structure analysis defining fracture frequency and aperture was evaluated for each boring. In data processing for each boring, structures were categorized into two basic types; closed or filled fractures or joints, and open or partially open fractures. Statistical data for each fracture type were catalogued along with stereographic projections of each fracture type.

The differentiation of the fracture type and statistical information such as fracture frequency and aperture is useful information because, as a general rule, the frequency and characteristics of fractures may help identify zones with greater hydraulic significance. These borings were drilled entirely within a crystalline granitic rock environment. The structure frequency distribution was relatively consistent in each boring with depth; however, a significant difference in orientation (mean dip and strike) was noted between wells. The mean fracture dip and strike in CDOT ROW #1 was 49.4º and 263.5º. The mean fracture dip and strike in Midway #1 was 51.2º and 258.7º. However, the mean fracture dip and strike in Dew Drop #3 was 39.1 and 84.8º.

Fluid Electrical Conductivity and Temperature

Borehole fluid electrical conductivity (FEC) and temperature were logged under ambient conditions. FEC and temperature profiles were similar for each well. The temperature varied between 5.5º C and 8º C across the entire length of the boreholes. The FEC of borehole fluid in each well ranged from a low of about 350 µS/cm to about 400 µS/cm.

Packer Pressure Testing

Packer pressure testing was conducted in CDOT ROW #1. The results of the packer pressure testing in this well suggest that water-bearing fractures in the lower interval of this well may be in hydraulic communication with and draining to the Big Five Tunnel. This data will be used during the detailed design to estimate the bulk hydraulic conductivity of the bedrock for the purpose of estimating groundwater flow velocities.

Treatability Testing

AMEC completed a bench-scale treatability study to evaluate lime (calcium hydroxide, $Ca(OH)_2$) and caustic (sodium hydroxide, NaOH) as neutralizing chemicals for the acidic mine water. The study evaluated chemical dose rates, the sludge volume produced, and treated water quality. In addition, AMEC geochemists studied the potential effects of adding an organic substrate to the water to establish reducing conditions and promote sulfate reduction and metals precipitation.

The neutralization tests showed that excellent water quality can be produced with lime or caustic treatment. The lime consumption rate was on the order of 0.25 g/L $Ca(OH)_2$ and the solids production rate was approximately 0.20 g/L. The caustic consumption rate was on the order of 0.30 ml/L of a 50% NaOH solution and the solids production rate was the same as with lime. The quality of the treated water was similar for both alkalis evaluated. Using the lowest pH set point tested, the concentrations of heavy metals

– Al, Cu, Fe, Pb, and Zn – were either non-detect or the removal efficiency was greater than 80 percent and increased with pH. Nickel removal efficiencies were low at the lower range of pH values tested, but increased significantly with an increase in pH. The manganese concentration remained near 2 mg/L even at pH 9.5, the highest pH tested. The low alkali consumption rate suggests that the reagent costs for an efficient treatment of the mine pool is relatively low, regardless of the alkali used.

A simple alkali injection system (no mixing) was evaluated. It was determined that such a system may be economical, but carried a risk that pockets of high pH would form due to the density of the alkali solutions. These effects could be mitigated by mixing that occurs while the mine pool is forming, but would be problematic as a long-term remedy when the mine pool is full and quiescent.

The geochemical equilibrium model PHREEQC was used to simulate an *in situ* sulfate-reducing bioreactor. In the model, the initial mine pool chemistry (pH = 3.08) was first adjusted to a pH of 6.0 using sodium hydroxide, and the common aluminum and iron hydroxide minerals were allowed to precipitate. The stepwise addition of organic carbon in the presence of the precipitated metal hydroxides was then simulated, and metal sulfide minerals (e.g., FeS_2, ZnS, NiS, etc.) were allowed to precipitate if they became oversaturated. The model predicts that a mine water concentration of approximately 350 mg/L of organic carbon would be required to precipitate the majority of the dissolved iron, cobalt, copper, cadmium, and lead as metal sulfides. The pH was predicted to remain near-neutral (6.6) with a drop in the oxidation-reduction potential to -180 mV. The concentrations of iron, cobalt, copper, cadmium, and lead are predicted to be reduced significantly. Aluminum and manganese concentrations were not affected. Sulfate was predicted to decrease from 1,005 mg/L to 850 mg/L with production of 9.9 mg/L H_2S due to sulfate reduction.

<u>Other</u>

Other testing was conducted during the pre-design investigation, including adit flow measurements and mine water quality sampling, seep reconnaissance and quality evaluations, geotechnical evaluations in the Big Five Tunnel, water level packer testing, tracer studies, and cultural resources surveys.

REMEDY EVALUATION

AMEC evaluated several options for the main components of the remedy. A detailed discussion of some of the components is provided below.

<u>Bulkhead</u>

The purpose of the bulkhead is to retain an underground mine pool with a maximum head of approximately 250 feet (747 kPa) for a relatively long design life of 50 years or more. The bulkhead should be leak free, although preliminary testing indicates that seepage through the surrounding rock is likely. The materials of construction of both the bulkhead and flow-through piping must be resistant to corrosion and chemical attack under both acidic and alkaline environments. AMEC evaluated three bulkhead types – a concrete mass plug, an anchored concrete plug, and a steel bulkhead.

<u>Concrete Mass Plug</u>

A concrete mass plug is placed in one continuous pour and contains minimal to no steel reinforcement. They are typically used to resist the highest heads (100 to 1,000 kPa) and are classified as "permanent" to the extent this concept can be attained. Typically, their lifespan is considered to be 100 years (Lang, 1999). These structures are usually longer than a steel bulkhead structure because they rely on the length and strength of the concrete along the sides of the tunnel to resist hydraulic head and they are generally designed with an added safety factor of 2.0. While increasing the cost, the additional length also provides better control of the hydraulic gradient along the bulkhead. The additional length provides a disadvantage because it is difficult to contact grout the area around the concrete, creating low angle intercepts at areas of concern.

Anchored Concrete Bulkhead

An anchored concrete bulkhead can be used to reduce the length and therefore the amount of concrete needed for bulkhead construction. This type of bulkhead employs tendon anchors that extend from the downstream face of the bulkhead into the surrounding host rock, ideally beyond any fracture zones where adequate anchorage and reduced exposure to acid water can be attained. Concrete plugs, whether anchored or not, are generally used to resist high heads (100 to 1,000 kPa) and have a lifespan of up to 100 years.

Steel Bulkhead

Steel bulkheads are not commonly used for the permanent retaining of high head mine pools. One concern is that the steel sections would be very large to resist the bending moment and as a result they would prevent efficient movement of the sections into the mine. Constructing them in the confined space of the tunnel would also be difficult. In addition, the metal would have to be highly corrosion-resistant to both acidic and alkaline chemical attack – possibly necessitating the use of exotic metal alloys.

AMEC also considered adding an engineered bulkhead door as an option to a steel bulkhead. The purpose of the door would be to help understand the performance of the treatment or to conduct maintenance, if needed. The door would have to meet all the requirements for strength and leakage that the bulkhead is designed to; however, the door would be a potential weak point in the system. Submarine doors were considered since they are capable of resisting high heads; however, the door would have to swing into the tunnel and may be blocked by sludge or other materials. In addition, opening this type of door could be hazardous to personnel, particularly if a significant quantify of sludge was impounded behind it. Therefore, a door was not included in the bulkhead design.

Selected Bulkhead

A concrete mass plug is the recommended bulkhead type for use at the Site. A steel bulkhead is not suitable for the conditions anticipated. An anchored bulkhead was considered, but was not selected because of the added cost of placing anchors in unfractured rock and away from potential AMD. The recommended bulkhead design includes flow-through pipes and supports to control the mine pool elevation and provide a means of mine pool recirculation, as needed for the selected treatment alternative. The piping will also be equipped with valves, pressure sensors, and sampling ports to provide information about the mine pool at the bulkhead.

Chemical Usage

Calcium hydroxide (lime) and sodium hydroxide (caustic) were evaluated for neutralizing the mine pool as part of the treatment system. In the treatability study both chemicals were identified as suitable materials for neutralization and both are commonly used, readily available, and relatively inexpensive. Because it is delivered and stored as a concentrated liquid and is a hazardous chemical, sodium hydroxide has more onerous storage requirements. However, neutralization chemicals are expected to require only temporary onsite storage (days to weeks). In addition, relatively small quantities of caustic will be required, such that it can be readily delivered in drums or totes. The advantage of sodium hydroxide is that it can be precisely metered and can be applied as a liquid rather than as a suspended slurry. Although lime may provide some excess alkalinity, the overall advantage is not significant enough to justify the handling requirements. In either case, in-mine mixing/recirculation is recommended to distribute the neutralization chemical throughout the treatment zone.

Sodium hydroxide is the preferred neutralization chemical because it is easy to use, requires less equipment, and the cost is expected to be only nominally higher than lime. Mixing/recirculation is recommended so that pockets of dense, highly concentrated caustic do not form. Based on the treatability testing approximately 0.3 mL/L of 50% sodium hydroxide is needed to neutralize the mine pool. Due to site conditions and the freezing point of 50% sodium hydroxide, the use of approximately 0.6 mL/L of 25% sodium hydroxide is recommended.

As an alternative to providing on-going treatments of the mine pool with caustic, AMEC evaluated placing a limestone bed behind the bulkhead to provide a long-term source of alkalinity. This limestone would be expected to dissolve slowly over time to provide long-term treatment of AMD near the bulkhead. Although some armoring of the limestone is expected, the residence time of the treatment zone is expected to be long enough to provide adequate dissolution and treatment. If operations require the slow release of water through the bulkhead, this limestone mass would likely be sufficient to neutralize the mine pool as it migrated through this zone.

Aeration

Iron concentrations are estimated to be approximately 50 mg/L in the mine water and dissolved oxygen (DO) concentrations range from 4 to 6 mg/L. Based on a conservative estimate of 4 mg/L of DO, it is calculated that the alternatives relying on neutralization require approximately 2 times more oxygen than is available to fully precipitate iron hydroxides. A lack of oxygen during the neutralization treatment may result in the precipitation of ferrous iron compounds that will not provide effective co-precipitation of other metals such as arsenic, cadmium, and manganese. In addition, ferrous iron compounds are less stabile and may resolubilize as the pH drops (i.e., in Left Hand Creek). As a result, alternatives with neutralization as the primary treatment step will include a means of oxygenation (either aeration or liquid oxidant injections).

Aeration is the preferred choice for oxygenation, since oxidant injections would require purchasing chemicals and may require the storage of hazardous chemicals. Air compressors are relatively cheap and easy to obtain, but the power requirements and the effects of operating the compressor at high elevations would need to be accounted for. Venturi aerators are passive, mechanical aeration systems, and therefore they do not require additional power (beyond that required to operate a recirculation pump). A venturi is the preferred aeration system, because a recirculation system was ultimately included in the design.

Power and Communications

AMEC evaluated the use of solar power to operate the monitoring and recirculation equipment. The design included a recirculation system that would operate only during daylight hours and would drain at night to prevent freezing. After careful consideration, it was determined that the solar power system would need to be too large to include sufficient backup power (using batteries) to maintain monitoring and communications. The system could also have reliability issues due to low solar angles in winter, and the heavily forested and mountainous terrain.

The design ultimately included bringing power to the communications shed located near the Big Five Tunnel Portal. Most of the power needs of the remedy will be met by power from a transformer; however, the water quality monitoring systems will be operated using solar power. The water quality systems are too remote to bring power to each station and burying power lines deep enough to meet the electrical code would be cost prohibitive and may disturb nearby cultural resources. Water quality equipment will collect and transmit data on-Site via radio signal. Data will be transmitted off-Site via cellular or satellite uplink.

In Situ Treatment

AMEC evaluated three types of in situ treatment – caustic injection with mine water recirculation, a sulfate-reducing bioreactor, and placing a limestone bed behind the bulkhead.

Caustic Recirculation System

The recirculation system would consist of an extraction point at the bulkhead and a re-injection point at Dew Drop #3, which is an upgradient boring that intercepts the Big Five Tunnel. Piping for the recirculation system would be buried to protect it from vandalism and freezing. The system would also include a venturi aerator to oxidize iron and a port for caustic injections.

Benefits

- The recirculation system would allow the treatment zone to extend beyond the collapse of the tunnel and would provide uniform neutralization throughout the treatment zone.
- Following the initial water treatment, this larger treatment zone may result in less frequent rounds of caustic recirculation as water leaks or is released from the mine pool.
- Water discharging through the bulkhead is expected to be of good quality.

Disadvantages

- Installing a pipeline in a mountainous area with shallow bedrock may be costly and time consuming.
- The potential requirement to continuously release water through the bulkhead would result in ongoing caustic of treatment.

Passive Limestone System

The passive limestone system would consist of providing an initial caustic dose while the mine pool is forming, and then providing a solid, fixed, long-term source of alkalinity consisting of a mass of crushed limestone rock behind the bulkhead.

Benefits

- Significant cost savings would be realized because a recirculation system and ongoing caustic additions are not needed.
- Ongoing maintenance to maintain elevated pH conditions will be reduced.
- Water discharging through the bulkhead is expected to be of good quality.

Disadvantages

- An air compressor and power system would be needed to provide periodic aeration for the foreseeable future. If a venturi is used as in the recirculation system, then power would be required to operate a recirculation pump.

Sulfate-Reducing Bioreactor

Developing conditions for a sulfate-reducing bioreactor environment in the mine pool immediately behind the bulkhead was considered. The intent would be to generate a self-sustaining population of microbes that would reduce sulfate to sulfide in an anaerobic, low ORP zone. The sulfide produced would quickly bind metals and precipitate as metallic sulfides. The microbial population will require a source of energy such as a solid organic carbon substrate. Initially, the mine pool would be dosed with caustic to bring the pH to near-neutral (approximately 6.0 to 6.5) to allow the microbes to establish and acclimate in sufficient mass to adequately treat the water. Once established, the bioreactor would be capable of producing sufficient alkalinity to maintain the mine pool at near neutral pH.

Benefits

- Cost savings would be realized because a recirculation system and ongoing caustic injections would not be needed.
- A long-term source of power would not be needed.

- Water discharging through the bulkhead is expected to be of good quality.

<u>Disadvantages</u>

- High iron and manganese concentrations from the precipitates that are already present in the mine could cause the reaction to stall at metals reduction (before it reaches sulfate reduction), which would solubilize iron, manganese, and co-precipitated metals such as arsenic, mercury, and cadmium.
- This alternative would require a constant release of water from the bulkhead to keep sulfate-containing water flowing to the treatment cell from distant locations in the mine workings.
- A stagnated mine pool could consume the available sulfate and possibly transition to methanogenesis and produce methane in the mine.
- Stainless steel piping cannot be used in the bulkhead; however, the thermal expansion and contractions of HDPE piping may create voids in the bulkhead that will allow leakage.
- Reduced metal sulfide solids that are allowed to discharge from the tunnel may re-oxidize and become soluble metals under atmospheric conditions. The release of metal sulfides may be prevented by design.
- Possible depletion of the solid organic substrate would limit treatment effectiveness over time.

Monitoring

Frequent data collection is required in the time period immediately following remedy construction, particularly as the mine pool fills. Automated systems have high capital costs, but can collect much more data over a given time period than manual collection allows. A large dataset will help to identify background conditions and reduce noise in the data to allow the detection of small changes in groundwater. Automated systems can collect data daily, or more frequently, while manual data collection may only be practical at weekly intervals. As the mine pool stabilizes, the frequency of manual measurements may be reduced to monthly data collection; however, automated systems can collect data every few days and can be left unattended for long periods between systems maintenance visits.

The long-term monitoring equipment will consist of a mix of monitoring wells to monitor groundwater and the mine pool, water quality meters, and electrical resistivity tomography (ERT) arrays. The ERT arrays and water quality meters will be automated and will be supplemented by periodic manual monitoring of borings, streams, and seeps. Data from the ERT arrays, water quality meters, recirculation system and bulkhead monitoring equipment will be collected and transmitted via cellular or satellite service. A shed near the Big Five Tunnel portal will house controls and communications equipment.

<u>ERT Arrays</u>

ERT is a geophysical technique used to image the subsurface from voltage and current measurements (measurements of resistivity) made at the surface or from electrodes placed in boreholes. At the Site, ERT measurements will be used to identify groundwater movement and to help identify potential locations of surface expressions of groundwater. It may also be possible to detect changes in groundwater chemistry (i.e., an increase in conductivity). Both borehole ERT arrays and shallow ERT arrays are included as part of the long-term monitoring system. An array is simply a string of electrodes that allow remote monitoring of a large area. The shallow arrays are buried in shallow trenches along the ground, while the borehole arrays are placed on centralizers fastened to casing inside a borehole.

As shown in Figure 3, two surface arrays will be installed east of the Peak to Peak Highway and one will be installed along the projection of the Big Five Tunnel. Wells will be installed and instrumented near Midway #1 and near CDOT ROW #1. Dew Drop #1 and Dew Drop #2, which are already instrumented, will also be used to collect ERT data.

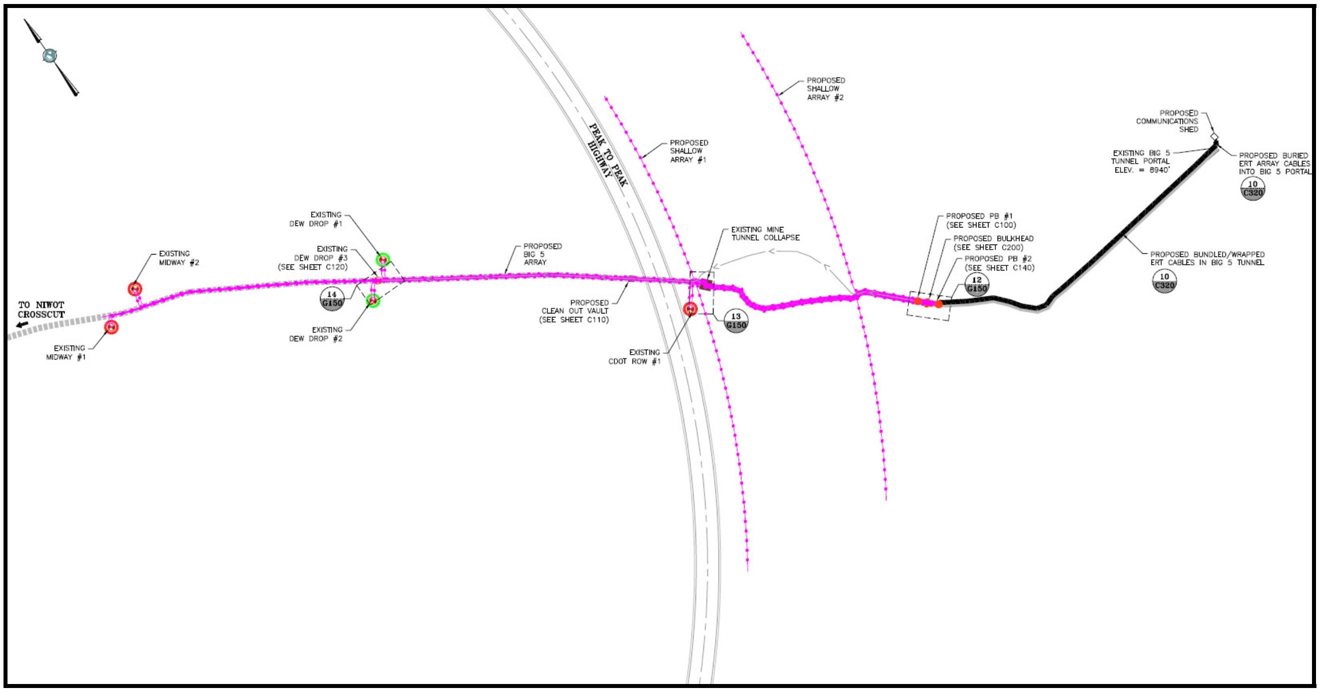

Figure 3 – ERT Array Layout

Water Quality Meters

Water quality meters are included to collect groundwater and mine pool water quality data without making frequent visits to the Site. The water quality meters consist of a water quality probe, battery, solar panel, and telemetry system that require minimal maintenance. The probes are self-contained and will collect and transmit data on a pre-set schedule. The probe will measure temperature, pH, DO, ORP, and water level.

SELECTED REMEDY

The subsurface remedy consists of the following key components:

- A flow-through concrete bulkhead (plug) and associated shotcrete and pressure grouting to prevent the discharge of AMD from the Big Five Tunnel. Blocking the discharge will create a pool in the mine workings that can be treated in situ. In addition, flooding a portion of the mine workings will limit oxygen availability and thereby reduce future AMD generation.

- Limestone rock placed behind the bulkhead that will provide long-term residual alkalinity to treat the mine pool at its most shallow location, where seeps and leakage are most likely.

- A recirculation system will be installed to extract water from behind the bulkhead and inject it in an upgradient portion of the mine workings. Recirculation of the mine pool serves three purposes:

  1. A venturi aeration system will operate as part of the recirculation system to supply limited amounts of oxygen to the mine pool to enhance metals precipitation and improve treatment efficiency.

2. The recirculation system can be used to inject chemicals (caustics) into the mine pool if the limestone is inadequate for treatment. An initial dose of caustic may also be added to the mine pool as it forms.

3. Recirculation will allow for a larger section of the mine pool to be treated to reduce impacts to potential surface seeps.

- A long-term monitoring system will be established to remotely monitor the mine pool and surrounding groundwater. The long-term monitoring equipment will consist of a mix of monitoring wells to monitor groundwater and the mine pool, groundwater quality monitoring equipment, and electrical resistivity tomography (ERT) arrays. The goals of the monitoring program are to identify the conditions in the mine pool, establish the ongoing efficacy of the remedy, assess the need for additional treatment, and establish if the mine pool is negatively impacting nearby groundwater or surface water.

- Power at the Site will be delivered by the placing a single phase, 230V transformer near the Big Five Tunnel portal. Remote equipment, such as the water quality meters, will be solar-powered.

AMEC is currently evaluating potential impacts to cultural resources near the Site and finalizing the design for the preparation of bid documents. System installation is tentatively planned for the summer of 2014.

REFERENCES

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