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Analysis of Molybdenum Sources, Water Management and Treatment Alternatives

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Prepared for:

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Sign-off Sheet

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Executive Summary

The purpose of this report is to address molybdenum sources, water management and treatment alternatives associated with the Climax Mine (“Climax”). These topics are more fully set forth in the Colorado Water Quality Control Commission (“WQCC”) Statement of Basis and Purpose (SBP) in Regulation 33 (5 CCR 1002-33.60). While the scope of the SBP encompasses all constituents that are addressed by water treatment, the primary focus of this analysis is molybdenum. Stantec Consulting Services, Inc. (Stantec) was retained to conduct studies and evaluate the topics raised in the SBP. This analysis presents the outcomes of the investigations and evaluations conducted by Stantec.

Climax is a molybdenum mine that has been developed over the course of approximately 100 years in a molybdenum-rich ore body in Lake County, Colorado. Water quality monitoring at the facility has identified multiple locations within the mine where the mining process was not able to completely extract molybdenum from the ore and that contribute molybdenum to mine waters that eventually are discharged from the site following treatment at two on-site facilities. Climax restarted mining in 2012 using an open pit mining method to extract ore for processing at the mill. A portion of the ore body has oxidized over geologic time such that there are periods of time when the ore processed at the mill contains varying percentages of oxidized ore. Since the re-start of the facility in 2012, the likelihood of encountering oxidized ore has increased. As a result, the amount of molybdenum introduced to the mine water management system from milling of ore has increased and is now recognized as another source of molybdenum that influences discharge water chemistry.

Currently, the active water treatment management system involves two stages of pH adjustment to remove metals associated with acidic mine drainage. The first stage of water treatment is at the Sludge Densification Plant (SDP) where most metals associated with acidic drainage are removed at a pH of about 7. The second stage of water treatment is completed at the Property Discharge Water Treatment Plant (PDWTP), where more metals (primarily manganese) are removed at a pH of about 10. The treated water from the PDWTP is discharged above Climax Outfall 001A. Currently, some molybdenum removal occurs when effluent from the SDP is discharged to Tenmile tailings storage facility (TSF) that, periodically, contains low pH water. Mixing of the two flows causes precipitation of ferric oxyhydroxide when the pH is about 5, which causes dissolved molybdenum to adsorb to the iron solids and settle in the tailings pond. Thus, while there is some removal of molybdenum in the water management system, a specific and engineered process for molybdenum treatment does not currently exist.

Control and/or management of molybdenum at Climax could potentially occur at three points in the mine operation: (1) in the mining/milling process, (2) within the mine water management system after oxidized ore tailings has been deposited, or (3) at the outlet of the mine water management system at the PDWTP. Within the context of the three overarching categories of control, Stantec developed an initial set of options that incorporate combinations of water management, optimization of water treatment, maximizing available blending, and water treatment influent control for limiting the concentration of molybdenum in water discharged from Climax. Stantec also included alternatives addressed in the WQCC Policy 13-1 for Discharger Specific Variances for a total of 31 options considered under the provisions of the SBP. These initial options were evaluated against a set of criteria to reduce the number of options for further consideration. Six options, with sub-options, were identified for more detailed evaluation.

Two of the six remaining options would require major changes to the water management system. Each option was evaluated first to make sure requirements related to hydraulic demands (i.e., meet peak flows) of the water management system could be met while maintaining tailings impoundment water levels within limits established for TSF operations. Neither of the options requiring change of the current configuration of the water management system were able to meet the hydraulic demands of the water management system and maintain tailings impoundment water levels below the normal operating upper limit. Therefore, these two options will not be further evaluated in cost estimating.

The remaining four options, all but one of which would modify operations at the PDWTP, were evaluated further to develop cost estimates for implementation and operation. Summary costs for the retained options are shown in **Table EX-1**. As described in more detail in this document, all options listed in **Table EX-1** will require additional testing of the chemical process and engineering design of the infrastructure before a final selection could be made by Climax. The intent of this information included in **Table EX-1** is to support the WQCC in reducing uncertainty related to the water quality standard for molybdenum to support a water supply use category.

Table EX-1 Summary of Estimated Costs in 2019 Dollars for Retained Options

Option	Capital Estimate	Annual Operating Estimate	Life Cycle Estimate	Projected Effluent Mo (µg/L)(1)
9 – Buildout Full-Scale Mo Removal Plant(2)	$79,652,000	$2,829,000	$127,100,000	200 to 500
10a – Optimize Existing PDWTP	$26,202,000	$615,325	$35,522,500	200 to 500
10b – Convert Existing PDWTP for $PbMoO_4$ Precipitation	$3,600,000	$1,700,000	$32,638,500	500 to 5,000
13 – Buildout **50%** Capacity Mo Removal Plant	$52,551,000	$1,556,000	$78,137,500	1,000 to 5,000
13 – Buildout **25%** Capacity Mo Removal Plant	$34,671,000	$870,000	$48,977,000	1,000 to 10,000
14 – Reduce Mo in the Tailings Slurry Pipeline	$7,022,000	$6,269,000	$109,988,500	5,000 to 10,000

Notes: (1) projected concentration ranges may change as additional information becomes available, (2) Source of costs for Option 9 are Golder, 2017 escalated to 2019 dollars.

Abbreviations

AACE	American Association of Cost Estimators
ac-ft	Acre-foot
ARD	Acid Rock Drainage
CDPHE	Colorado Department of Public Health and Environment
DRMS	Colorado Division of Reclamation, Mining and Safety
DSV	Discharger specific variance
GPD	Gallons per day
gpm	Gallons per minute
mg/L	Milligram per liter
μg/L	Microgram per liter
Mo	Molybdenum
NaHS	sodium hydrosulfide
PDWTP	Property Discharge Water Treatment Plant
TR	total recoverable
TSF	Tailings Storage Facility
SBP	Statement of Basis and Purpose
SDP	Sludge Densification Plant
WET	Whole Effluent Toxicity Testing
WQBEL	Water Quality Based Effluent Limit
WQCC	Colorado Water Quality Control Commission
WQCD	Colorado Water Quality Control Division

1.0 INTRODUCTION

1.1 STATEMENT OF BASIS AND PURPOSE

Climax Mine has been in operation for over 100 years with the purpose of extracting molybdenum from mined ore. Climax resumed mining operations in 2012 after a long hiatus of care and maintenance. Mining results in the accumulation of mine-related materials in the form of waste rock and tailings. A portion of the molybdenum in the ore remains with the tailings and is subject to mobilization after final deposition of the tailings. Additionally, variations in the mineralogy of the ore (oxidized versus sulfide) also contribute to the occurrence of molybdenum in mine water. Because Climax is located at high elevation, the annual hydrologic cycle includes a large influx of water in the spring when the annual snowpack melts. Other downstream users own the right to some of the snowmelt runoff. As a result, Climax must release water from the mine to meet water rights obligations, manage the mine water balance, and maintain the overall stability of mine facilities, especially the tailings impoundments. Thus, with a portion of molybdenum contained in ore entering the mine water management system and the need to discharge water from the mine, molybdenum is discharged from the mine into the receiving water of Tenmile Creek.

The currently applicable molybdenum standard in Blue River Segment 14 (COUCBL 14) is 210 µg/L with a temporary modification of “current conditions.” This temporary modification was adopted by the WQCC in 2014 in recognition of the uncertainty regarding the water quality standard necessary to protect the water supply use. The WQCC held a hearing in January 2018 concerning extension of the temporary modification. The Statement of Basis and Purpose (SBP) associated with that hearing included a list of issues for Climax to address in order to inform the Commission as to whether attainment of the underlying standard of 210 µg/L is technically and economically feasible. This report does not address the uncertainty associated with the 210 µg/L molybdenum standard, i.e. the scientific justification of the molybdenum standard to protect the water supply use. The focus of this report is to present results of investigations addressing the following specific items listed in the SBP:

Climax will conduct investigations for molybdenum including:

- Identification of sources
- Influent control measures
- Investigation of potential treatment alternatives
- Treatment optimization
- Available blending

Climax will identify:

- Treatment options
- Source controls

- Water management alternatives
- Expected effluent quantity and quality that could be achieved with each alternative
- Estimate cost of each alternative

1.2 PROJECT WORK PLAN

Stantec Consulting Services, Inc. (Stantec) was retained to conduct investigations related to topics outlined in the SBP. The work plan was developed in a phased approach with the first phase focusing on identification of molybdenum sources at Climax and the second phase addressing the remaining items identified in the SBP. This report addresses all items of the WQCC SBP, including projections of effluent molybdenum concentrations and costs associated with retained options.

1.3 CURRENT WATER AND CHEMICAL MASS MANAGEMENT AT CLIMAX

The water management system at Climax is complex consisting of 42 miles of pipelines, 11 pump stations, two barge pump stations, and two water treatment plants (**Figure 1**). Major drivers or constraints in the water management system include: (1) limitations on storage of water related to water rights obligations, (2) safe working volumes in tailings impoundments, (3) mill water demands based on ore through-put, (4) seasonal inputs of water during the normal annual cycle of snowpack development (October to April) and associated snowmelt (April to June), and (5) the need to maintain storage capacity for extreme precipitation events or operational upsets. Tailings are currently deposited in the Mayflower tailings storage facility (TSF), and under the current mine plan, tailings will continue to be placed in the Mayflower TSF for the foreseeable future. Depending on the demand for water at the mill and time of year, reclaimed water from the Mayflower TSF decant pool is pumped back into the mill circuit (via Robinson Reservoir) or to the Property Discharge Water Treatment Plant (PDWTP) where the water is treated and discharged to upper Tenmile Creek at Outfall 001A. The PDWTP is sized to handle a peak flow of 14,000 gallons per minute (gpm), which occurs during the spring snowmelt period. Design of the Sludge Densification Plant (SDP) was for a routine flow of 6,000 gpm; however, the plant is operated most efficiently at about 5,000 gpm.

The two water treatment facilities at Climax are operated to produce different pH adjustments to remove various constituents in waters derived from mine facilities. The first stage of water treatment occurs at the SDP, which is located adjacent to Tenmile TSF. Water treatment at the SDP addresses the portion of the overall mine water that is acidic (as acid rock drainage [ARD]) through a process of lime neutralization (at pH 7) with solids separation via a high-density sludge system. Treated water is discharged to the Tenmile TSF decant pool and residual solids are discharged to a separate solids storage facility located adjacent to the treatment plant. There are periods of the year, primarily during snowmelt, when the influent flow rate is greater than the design capacity of the SDP and the excess ARD by-passes the SDP and flows into the Tenmile TSF. By-pass of excess water at the SDP is by design and excess water is treated with lime before reporting to Tenmile TSF. Lime is added to the by-pass flow to initiate the neutralization process as the water flows into Tenmile TSF. The effluent from the SDP (neutral pH water) and the neutralized by-pass water mix in the Tenmile TSF, resulting in formation of iron hydroxide solids that adsorb molybdenum when the pH in Tenmile TSF is around 5. While not part of a specific engineering design, the additional treatment occurring in the Tenmile TSF, during periods when the specific pH condition exists, results in reduction of the concentration of molybdenum reporting to the PDWTP, where the second stage of water treatment at Climax occurs.

Water reporting to the PDWTP is treated at pH 10 to remove residual metals, primarily manganese, with pH then adjusted to circum-neutral prior to discharge above Climax Outfall 001A that forms the beginning of Tenmile Creek (Blue River Segment 13). Flows at the PDWTP can be as high as the design capacity of 14,000 gpm during the spring snowmelt. Solids generated by the treatment process are stored in a facility located adjacent to the Mayflower TSF.

Upland flow, which serves as the main source of water for freshwater blending, originates as snowmelt or runoff from precipitation. The upland flow is routed around the mine facility by an interceptor system that discharges and comingles with PDWTP effluent in Tenmile Creek above Outfall 001A. The snowpack and direct runoff from the mine facilities may be impacted through contact with mine materials and is captured in the mine water management system. A portion of this water is used for mineral processing, but most of the water must be discharged from the site either to meet water rights obligations or because there is insufficient storage volume available. The current water management system at Climax provides as much freshwater blending as is possible between treated mine water and upland flow from the interceptors, given other constraints in the water management system. Thus, during certain times of the year, freshwater blending has a strong influence on the chemistry of water discharged from Climax; however, the nature of precipitation inputs during other times of the year (i.e., late summer, fall and winter) limits the effect of freshwater blending on discharge water quality. The potential for blending within the mine water management system is limited by the need to manage mine water flows (e.g., ARD), availability of storage volume, requirements to satisfy water rights obligations, and the need to meet water demands for the mill.

1.3.1 Constraints on Water Management

There are several constraints on the site-wide water management system at Climax that influence the volume of water that can be stored on site and how/when water must be discharged from the facility to Tenmile Creek via the PDWTP and Outfall 001A.

On an annual basis, the principal input of precipitation is from accumulation of snowpack and then snowmelt in the spring. The typical annual volume of snowmelt contributed to the Climax water management system that must be either used by the mine or treated and discharged from the PDWTP is around 6,750 ac-ft when the mine is in production. However, Climax has discharged close to 10,000 ac-ft during high snowpack conditions. In contrast, the total maximum storage volume in surface facilities at Climax (i.e., Mayflower and Tenmile TSFs and Robinson Lake) is variable, but on average 5,400 ac-ft. Thus, while snowmelt might be managed on site seasonally (i.e., zero discharge), the site has a net positive water balance and multiple years of snowmelt input cannot be stored. Annual excess water must be discharged from the site.

Climax is one of many water-users spanning three river systems (Tenmile Creek/Colorado River, Eagle River, Arkansas River) all of which are over-appropriated for water rights. Climax has water rights that allow the facility to operate, which means some water can be consumed, some water can be temporarily stored, and the rest of the water beyond the established water right must be delivered to the appropriate river basin. Because most of the mine facilities, especially those that store water, are in the Tenmile Creek drainage, the water rights constraints associated with the upper Colorado River basin have the most influence on water management at Climax. Climax can only divert the natural flow of Tenmile Creek or Eagle River when a senior water right is not in priority. Additionally, Climax may not generally divert or store water from November through March.

Snowmelt and rainfall runoff that contacts mine materials may not be discharged directly and is captured by the site water management system. However, snowmelt and rainfall that originates *outside* the Climax operation that would naturally report to the mine facilities, is diverted by interceptor channels located on the south, east, and west sides of the mine and discharged directly to the respective watershed. Additionally, some stormwater flows from the facility are discharged via outfalls identified and permitted under the facility stormwater permit (COR-040178).

The decisions Climax makes regarding the site wide water management system involve consideration of several, sometimes competing, factors including: (1) time of year, (2) status of water rights limitations, (3) volumes contained in storage facilities, (4) water demands of the milling process, and (5) water treatment limitations.

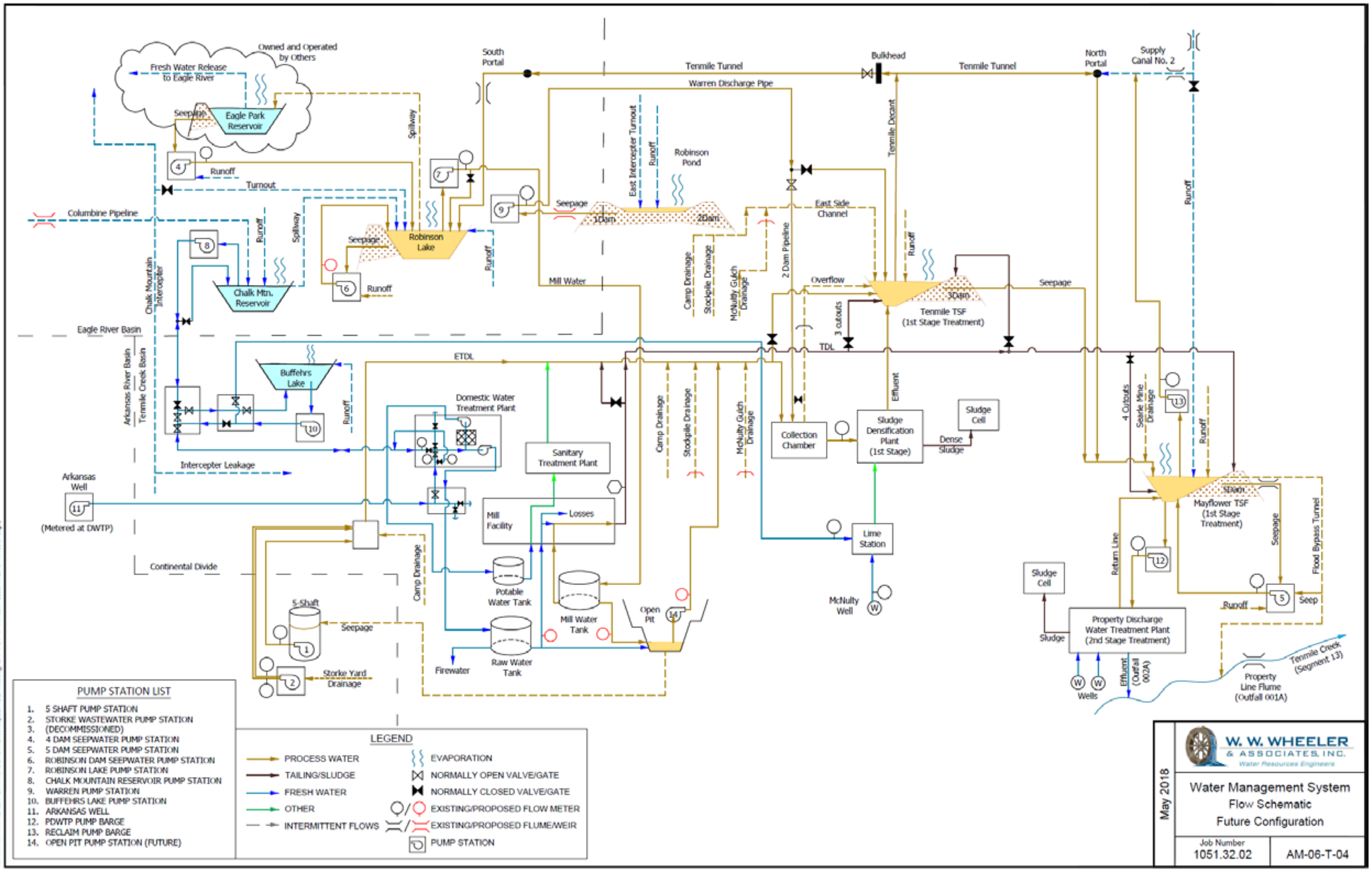

Figure 1 Schematic of the Climax Water Management System

2.0 SOURCE IDENTIFICATION

2.1 MINE FACILITY SOURCES OF MOLYBDENUM

Climax is a molybdenum mine that opened in 1915 and operated continuously from 1924 until the 1980s. The primary target mineral is molybdenite (MoS_2), which is a sulfide that can be separated from the host rock by crushing and grinding followed by froth flotation. The molybdenum concentrate is shipped from the facility for further processing. The residual ground rock (tailings) is transported to tailings storage facilities and deposited. The mineralogy of the tailings is a mixture of the host rock minerals (most abundant) and minor amounts of sulfide minerals (molybdenite and pyrite). Additionally, portions of the ore body at Climax have been subjected to natural chemical oxidation over geologic time and oxidized molybdenum also reports to the tailings. The oxidized minerals tend to be more soluble than un-oxidized sulfide minerals. In summary, because of the mining process, including rock excavation and milling, development of waste rock facilities, and creation of tailings storage facilities, there is some molybdenum everywhere, in every facility of the Climax Mine site.

Soluble molybdenum is transported from mine facilities by drainage induced mainly by infiltration of precipitation. The resulting seepage reports at the toe of facilities, where Climax collects and routes the seepage within the water management system. Much of the seepage from facilities at Climax is directed to the SDP for Stage 1 treatment. Because the soluble molybdenum generated within the Climax operation reports as facility drainage, the focus of the source identification is more on identifying what facilities produce the highest concentrations of soluble molybdenum. Additionally, because the mine is in active operation, most of the facilities that yield soluble molybdenum will continue to yield soluble molybdenum until final reclamation is implemented.

2.2 ANALYSIS OF SOLUBLE MOLYBDENUM SOURCES

Climax conducts water monitoring, including flow and chemistry, at multiple locations within the mine property. **Table 1** provides summary statistics (minimum, maximum, and average) for dissolved and total recoverable (TR) molybdenum at key internal locations for the recent period of active mining (2012 to 2017). Stantec used the available data “as-is” such that potential data outliers could exist in the data set. Stantec took this approach because the data were provided by Climax through the monitoring program and Stantec has no history regarding implementation of the monitoring program, QA/QC of laboratory data, or potential variation in facility operations. However, Stantec is confident that the total size of the data set is sufficient to yield reliable information about molybdenum sources at Climax.

The initiation of internal monitoring at Climax varies by location. In order to compare results for locations throughout the facility, Stantec focused the source identification evaluation on the period of data from 2015 to 2017. Averages of the flow record for the period 2015 to 2017 is reported in the summary table (**Table 1**), but the average chemical mass loading (concentration multiplied by corresponding flow) was calculated from paired data; that is, sampling events for which both flow and concentration are available. The average chemical mass loading was then calculated from the paired flow-concentration data set. Additionally, chemical mass loading was calculated for locations either where molybdenum is input to the water management system or at points of discharge (e.g., the PDWTP). Other locations within the water management system (e.g., the SDP and 10 Mile Riser) are summarized by concentration data because these internal sampling locations are points of throughput in the water management system and are not indicative of molybdenum sources.

Based on the data presented in **Table 1**, molybdenum sources were ranked by concentration and chemical mass loading (**Table 2**). In terms of chemical mass loading, the #1 Drop Box ranks as the principal source followed by the seeps (**Table 1**). As indicated in **Table 2**, the 3 Dam Seep and Warren's Pump Station (1 Dam Seep) rank highest in concentration. All sources listed in **Table 2**, except for the #1 Drop Box, report to the SDP for Stage 1 treatment of ARD. As previously described, the effluent from the SDP reports to the Tenmile TSF as does any SDP inflow in excess of the SDP capacity. The mixture of SDP effluent (neutral pH) and SDP by-pass (iron-bearing ARD) promotes formation of iron oxyhydroxide solids that, at times when the pH of water in Tenmile TSF is lower (4 to 5), removes soluble molybdenum by adsorption. However, the removal process occurs in an uncontrolled manner such that there is not consistent removal of molybdenum. The effects of the molybdenum removal reaction are reflected in the water chemistry recorded at the 10-Mile Riser (**Table 1**). While the SDP/Tenmile TSF system removes molybdenum, the process is uncontrolled, and therefore, is not considered an operable unit process for water treatment. Additionally, the Tenmile TSF is scheduled for closure. Any longer-term solution for management of molybdenum at Climax cannot rely either on the storage volume in Tenmile TSF or on the molybdenum removal in the SDP/Tenmile TSF process.

The seep sources listed in **Table 2** are mine features that will likely continue to act as sources of molybdenum until site reclamation is completed. Another source of molybdenum was recently evaluated that derives from the type of ore being processed, which is represented by values listed under #1 Drop Box in **Table 2**. Molybdenum in the ore exists in two chemical states: (1) as a sulfide mineral (i.e., molydenite) and (2) in an oxidized form. Both forms of molybdenum exist in the ore body with some parts of the ore body being more oxidized than other parts. Climax utilizes the industry standard flotation process to recover molybdenum-bearing minerals. Flotation is only effective for collection of sulfide minerals. Molybdenum-bearing oxidized minerals, which constitute a small and spatially distributed portion of the molybdenum in the deposit, are not recovered in the flotation process. When material with a higher degree of oxidation is processed, the resulting tailings becomes an important source of soluble molybdenum that affects the concentration of molybdenum in water reporting to the PDWTP. Analysis of the molybdenum concentrations, as well as additional laboratory testing of oxidized ore, indicates that approximately eight percent of the oxidized molybdenum in the ore feed dissolves during the milling and flotation process. In response to this recent information about oxidized ore, Climax has implemented a near-term method of source control by adopting a revised 2019/2020 mine plan that limits the percentage of oxidized molybdenum in the ore feed to the mill and thereby limiting the quantity of soluble molybdenum introduced to the mine water management system.

Table 1 Summary of Dissolved and Total Recoverable Molybdenum at Key Locations (2015-2017)

Location	Average Flowrate (gallons/day)	Molybdenum (Dissolved)				Molybdenum (Total Recoverable)			
		Min. (mg/L)	Max. (mg/L)	Average (mg/L)	Chemical Mass Loading (lbs/day)	Min. (mg/L)	Max. (mg/L)	Average (mg/L)	Chemical Mass Loading (lbs/day)
Warren's Pump(1)	1,299,000	0.3	19.7	5.2	---	11.4	47.4	18.0	198
3 Dam Seep	1,501,661	3.19	31.5	17.0	179	3.41	31.9	17.5	185
4 Dam Seep	N/A(2)	<0.02	0.02	<0.02	--	<0.02	0.14	<0.02	--
5 Dam Seep	1,672,000	0.0038	8.59	1.3	19	0.037	8.3	2.3	33
SDP Influent(3)	4,700,000	0.789	8.06	2.1	---	2.77	7.75	4.94	---
SDP Effluent(4)	4,700,000	0.417	2.49	0.98	---	0.61	97.6	7.50	---
#1 Drop Box	12,327,000	0.34	23.4	2.04	217	0.37	54.9	3.2	257
10 Mile Riser (North Portal)	6,176,00	<0.1	1.38	0.23	---	<0.04	1.43	0.29	---
PDWTP Influent(2)	8,996,000	0.41	2.58	1.38	---	0.46	2.64	1.42	---
PDWTP Effluent	8,996,000	0.439	2.53	1.36	94	<0.02	2.62	1.38	95
Interceptors	Not available	--	--	--	--	0.002	0.0279	0.012	--
Outfall 001	26,649,000	<0.02	2.17	0.61	97	<0.02	2.0	0.62	99

Notes:
Data summary corresponds to the 2015 to 2017 time period.
1 – Dissolved Mo data are limited to four measurements from 2011 to 2014.
2 – Flow measurement began in 2017, flow record too short to calculate a chemical mass loading
3 – Data summary for WTPs include only influent and effluent measurements made on the same day.
4 – Total Recoverable Mo in SDP effluent appears to be influenced by four outlier values than may indicate an upset condition.

Table 2 Ranking of the Sources at the Climax Mine Based on Highest Average Concentration and Chemical Mass Loading

	By Concentration		By Chemical Mass Loading	
Rank	Dissolved Mo	TR Mo	Dissolved Mo	TR Mo
1	3 Dam Seep	Warren's Pump Station	#1 Drop Box	#1 Drop Box
2	Warren's Pump Station	3 Dam Seep	3 Dam Seep	Warren's Pump Station
3	#1 Drop Box	#1 Drop Box	5 Dam Seep	3 Dam Seep

3.0 WATER AND CHEMICAL MASS MANAGEMENT OPTIONS

3.1 STRATEGY TO ADDRESS THE STATEMENT OF BASIS AND PURPOSE

Pursuant to the SBP, the WQCC requires Climax to consider measures that might be implemented to limit molybdenum concentrations in water discharged from the site, including source control, operational changes, blending, and removal through treatment. These measures differ among those that limit the MASS of molybdenum released into the system and those that lower the CONCENTRATION. As the chemical mass load and rate of water discharge vary seasonally, the options considered are likely to have different impacts on discharge water concentration at different times. As freshwater blending does not adequately address the concentration of molybdenum at downstream locations, the study focused on options for REMOVAL of soluble molybdenum from the system and thereby reducing the concentration of molybdenum discharged from Climax.

As identified in Section 2, the principal sources contributing to molybdenum in the discharge water include: soluble molybdenum in the ore that is mobilized during the milling process and transported in the tailings stream; and seepage from the TSFs. Source control then focuses in part on measures to capture and treat molybdenum in seepage and identifying options to control molybdenum as close to the mine/mill as practicable. Climax already implements measures to capture and treat for other metals in the seepage and to limit the mass of dissolved molybdenum released with the tailings stream.

Stantec reviewed the current water management plan implemented at Climax to determine if there might be ways to blend the various waters on the site, and thereby reduce the concentration of molybdenum. Such an evaluation necessarily considered the requirements to discharge certain quantities of water for the benefit of other holders of water rights and the available storage capacity at Climax. The current water treatment strategy at Climax is designed to address water quality concerns for constituents other than molybdenum such as iron, manganese, zinc, and other metals (e.g., cadmium). This current evaluation considers a range of controls that limit discharge of soluble molybdenum. Options considered include measures that address multiple elements of the SBP.

3.2 FRAMEWORK FOR OPTIONS IDENTIFICATION

The operation at Climax involves hauling ore from the open pit to the mill, crushing the ore, extracting molybdenum concentrate (sulfide molybdenum) by a flotation process, and disposing of the residual tailings in a storage facility. Not all rock extracted from the pit classifies as ore, and this overburden is deposited in the overburden storage facilities. Water is used to process the ore, float the concentration, and then to transport the tailings to the storage facility. Given the large quantities of ore processed, concomitantly large quantities of water are also used in the process.

Residual mining materials, either as tailings or as overburden, are exposed to precipitation and will remain exposed until mining ceases and these facilities are covered and reclaimed. Precipitation that infiltrates and percolates through the mine facilities transports trace amounts of molybdenum (and other constituents) based on the geochemical processes that affect reactive minerals stored in the facility.

While Climax is an active operation, the processes by which molybdenum is mobilized at mine facilities limit the options available to control molybdenum. Stantec initially identified options for molybdenum control without consideration of operational or other constraints that might hinder or prevent implementation of an option. However, further consideration of the options necessarily required acknowledgement of the constraints imposed by the mining operation such as the physical properties of mine materials, the need to maintain a site-wide water balance under a very broad range of seasonal conditions, water rights obligations, and operational requirements to maintain control of water levels in water storage facilities (i.e. tailings storage facilities).

3.3 PROCESS TO IDENTIFY, EVALUATE, AND SELECT OPTIONS

3.3.1 Consideration of the WQCC Policy 13-1 on Discharger Specific Variances

Climax and Stantec met with representatives from the Water Quality Control Division (WQCD) in early 2019, including representatives from the WQCD's engineering, assessments, and standards sections. The WQCD suggested that, in evaluating all potential options and alternatives, Climax refer to the WQCC's Policy 13-1, *Guidance for Development, Adoption and Review of Discharger Specific Variances*, which the WQCC revised following an administrative action hearing in January 2019.

As set forth in WQCC Policy 13-1, as well as WQCC Regulation 31 (5 CCR 1002-31), §§ 31.7(4) and 31.9(5), a discharger specific variance (DSV) establishes an alternative effluent value or narrative condition that takes the place of a water quality-based effluent limit (WQBEL) for a specific point source discharge. A DSV is appropriate when a facility has considered all other potential avenues for resolving a compliance problem, including whether a revised WQS is appropriate either statewide or for a specific waterbody (WQCC Policy 13-1, pp.7-8). Because there is significant uncertainty regarding the appropriate statewide standard, as well as the site-specific standard, for molybdenum to protect human health, and because review and potential revision of the water quality standard for molybdenum is currently underway, both Climax and the WQCD agreed it is premature for Climax to consider a DSV. However, following the Division's suggestion, Climax and Stantec have reviewed and incorporated elements of the WQCC Policy 13-1 in developing this report.

3.3.1.1 Criteria for a DSV

The WQCC expects that facilities proposing a DSV conduct a comprehensive alternatives analysis that demonstrates there are no feasible alternatives that would allow the regulated activity to proceeded without a discharger exceeding WQBELs (see WQCC Regulation 31, § 31.7(4)(a)). Additionally, the facility would need to demonstrate that attaining the WQS is not feasible based on the outcomes of three tests: (1) the limits of technology, (2) economics, or (3) other consequences tests (see § 31.7(4)(a)(i)). These tests are defined as follows:

- *Limits of technology test*: demonstration that attaining the WQS is not feasible because, as applied to the point source discharge, pollutant removal techniques are not available, or it is technologically infeasible to meet the standard.
- *Economics test*: demonstration that attaining the WQS is not feasible because meeting the standard, as applied to the point source discharge, will cause substantial and widespread adverse social and economic

impacts in the area where the discharge is located; considerations include factors such as cost and affordability of pollutant removal techniques.

- *Other consequences test*: human-caused conditions or sources of pollution prevent attainment of the use and cannot be remedied or would cause more environmental damage to correct than to leave in place.

3.3.1.2 List of Alternatives in WQCC Policy 13-1

WQCC Policy 13-1 sets forth a non-exhaustive list of potential alternatives that should be considered at a minimum in evaluating feasibility under the three tests listed previously. These include the following 15 alternatives:

1. Alternative locations for the discharge, including moving the outfall to a water body with more assimilative capacity;
2. Consolidation with other wastewater treatment facilities;
3. Reduction in scale of the proposed discharge or activity;
4. Water recycling measures within the facility;
5. Reclaimed water use (see Regulation 84);
6. Process changes, raw material substitution, or alternative technology that could minimize the source of the pollutant;
7. Standard treatment methods;
8. Innovative or alternative methods of treatment and advanced treatment, including new designs, stages, components, capacity for treatment plant replacement or upgrades of current plant;
9. Improved operation and maintenance of existing facilities in order to maximize treatment or removal of the pollutant;
10. Seasonal or controlled discharge options to minimize discharging during critical water quality periods;
11. Watershed trading;
12. Land application of wastewater;
13. Total containment of wastewater (i.e., zero discharge);
14. Any other alternative to minimize the effects of the proposed discharge or activity;
15. No action (maintain status quo).

Stantec evaluated these 15 alternatives based on their inclusion in WQCC Policy 13-1. See **Appendix A** for more detail related to the evaluation in the context of the tests outlined in the Policy as well as the selection criteria specific to the Climax operation. Several of these alternatives coincide with options considered by Climax (see Section 3.2.2), such as Alternative 8, innovative or alternative methods of treatment, and Alternative 9, improved operation and maintenance of existing facilities. However, other alternatives are outside of Climax's control, would be infeasible to implement, and/or would not result in any improvement in discharge water quality. This includes, among others, potential alternatives under Alternative 14, which could include evaluating the water quality improvement and feasibility of a complete cessation of mining as "any other alternative to minimize the effects of the proposed discharge or activity." In this example, cessation of the mining operation would result in a large economic loss, locally, statewide, nationwide, and potentially worldwide.

In the next section, Stantec discusses the approach taken in evaluating and narrowing down options for this alternatives analysis.

3.3.2 Climax Approach

Stantec's primary focus in this analysis is to develop treatment options to satisfy the WQCC's directive in its 2017 Statement of Basis and Purpose to facilitate the WQCC's task of resolving uncertainty associated with the molybdenum standard necessary to protect the water supply use in Blue River Segment 14. The WQCD suggested that Stantec consider a 20-year timeframe in its evaluation of treatment alternatives. Although the Basic Standards (WQCC Regulation 31) say that a 20-year timeframe should be considered in the determination of attainability of a classified use, this timeframe does not appear to be relevant or appropriate to the immediate task of resolving the uncertainty associated with the underlying molybdenum standard. In anticipation of the WQCC adopting a water quality standard protective of the water supply use, and that standard being applied to the discharge of water from Climax, an important consideration is the time to implement an option. With this background, Stantec focused more on options that could be implemented in a few years over options that might prove effective but require a longer period of time to prove out. Furthermore, the current mine life of Climax extends to 2039, which means any option requiring 10 to 20 years to be implemented would only become effective at the end of mining.

Climax has a long mining history with facilities (e.g. tailings storage facilities and waste rock storage) that have existed for much of the mining period. Operation and maintenance of mine facilities follow industry standards and good practice for engineering design and consideration of safety, especially prioritizing maintenance of facilities in a physically stable condition. Including TSFs, Climax implements strict conditions regarding the amount of water stored in the TSFs at any given time. Any potential option to limit the concentration of molybdenum discharging from Climax, regardless of method, will first be subject to consideration of the potential for the option to exceed the designated operational limits for a TSF (e.g., operating water levels). In addition to consideration of TSF operations, mine water management operations at Climax are subject to requirements related to water rights that include seasonal limits on storage. Finally, Climax is planning to close the Tenmile TSF, which means that any option for molybdenum control relying on water storage on the Tenmile TSF can only be short-term.

As noted previously, options to manage and limit molybdenum discharging from Climax can be classified under three principal categories: (1) options implemented in the mining and milling process (i.e., in the mine and at the mill), (2) options modifying the current water management system that could increase the potential for blending or modify the timing of discharge, and (3) options that modify or expand the existing water treatment operations. Options that are combinations of two or more of the main categories are also possible.

Review of the sources of molybdenum, the mine water management system, water treatment systems, and discussions with Climax personnel yielded multiple options for limiting discharge of molybdenum from Climax. Stantec described and evaluated the options to determine how each option might be implemented in the current water management system at Climax. **Table 3** summarizes the options considered by Stantec, including the DSV alternatives listed in Section 3.3.1.2, Stantec also classified each option according to how each option primarily addresses the requirements set forth in the WQCC's SBP. Selection criteria were developed to pare the original set of options to a smaller set that would have the best potential to be implemented and to reduce the concentration of molybdenum in discharge from Climax. The initial screening of options was completed with greater emphasis on technical considerations than on economics or cost. Cost estimates for selected options are addressed in Section 5.

Stantec considered the following selection criteria in evaluating the options:

- **Effectiveness** – assess how well the option limits concentrations of constituents (molybdenum and other metals) of concern in discharge from the mine
- **Time to Implement** – differentiate among options regarding the elapsed time between initiation of engineering design and final commissioning (considering also time for preparation, review, and approval of permits)
- **Cost Consideration** – a relative estimate compared to the cost estimate for the fully built out molybdenum treatment plant
- **Reliability** – degree to which an option has complete engineering control over chemical processes to produce a specified discharge water quality on a consistent basis
- **Operability/Process Control** – evaluate if the option is optimized to achieve desired results
- **Flexibility** – given the wide range of hydraulic conditions over the annual hydrologic cycle and variations in water chemistry, is the option capable of addressing the range of conditions
- **Waste Management** – options that include water treatment generate waste in the form of residual treatment solids that must be maintained in stable chemical conditions to limit mobilization of target constituents
- **Effect on Water Balance** – some options would require modification of the water management system, which could cause challenges in maintaining site-wide water balance
- **Hydraulic Capacity** – during the annual snowmelt, the water treatment system needs to be able to handle flows up to 14,000 gpm, options that modify the site-wide water balance must meet this requirement either directly or through on-site storage

Note that the selection criteria are focused on topics related primarily to implementation and effectiveness and do not consider potential issues related to operations of the TSFs or near-term plans to reclaim and close facilities (e.g., Tenmile TSF). Stantec first evaluated options under the criteria listed above to keep the pool of potential options broad. Stantec then evaluated the remaining selected options for meeting operational conditions for the TSFs and plans for near-term facility closure.

Table 3 Initial Options Matrix for Addressing the SBP

Category	Option	Method Summary	Principal SBP Element
Mine/Mill	1	Do not mine oxidized ore	Source control
Mine/Mill	2	Delay mining oxidized ore until molybdenum removal method in place	Source control
Mine/Mill	3	Recover molybdenum at mill and receive credits; metallurgical process	Water management/blending
Mine/Mill	4	Recover molybdenum at mill and receive credits utilizing resin ion exchange	Water management/blending
Mine/Mill	5	Dry stack or thickened tailings and treat water prior to using water for tailings slurry	Water management/blending
Mine/Mill	6	Install counter current decantation system to recirculate high molybdenum water; discharge tailings with low molybdenum water	Water management/blending

Table 3 Initial Options Matrix for Addressing the SBP

Category	Option	Method Summary	Principal SBP Element
Mine/Mill	7	Separate high molybdenum water and use the underground as reactor; blend high molybdenum water with 5-Shaft water and route underground	Water management/blending
Water Treatment/ Management	8	Tailings to Tenmile while oxidized ore is mined; Tenmile pool to Mill and SDP; SDP re-configured to pH = 4.5; SDP effluent directed to PDWTP.	Water treatment; Water management/blending
Water Treatment	9	Buildout PDWTP for molybdenum removal (per CH2M Hill design [2011]).	Water treatment
Water Treatment	10	All ARD to SDP; modify SDP operations to pH=10 for metals removal; SDP effluent to PDWTP for molybdenum treatment by either ferric adsorption or lead molybdate precipitation; adjust treatment plant flows as necessary to maintain water balance.	Water treatment optimization
Water Treatment/ Management	11	Modify SDP to pH = 4.5 for molybdenum removal; SDP effluent to PDWTP; flows with highest molybdenum go through Mayflower and Mill and become the influent to the SDP.	Water treatment; Water management/blending
Water Treatment/ Management	12	ARD and Tenmile to SDP; modify SDP operations to pH = 10 for Mn; SDP effluent directly to modified PDWTP for molybdenum treatment at pH 4.5; supplemental flow from Mayflower to PDWTP to maintain water balance; Mill to Mayflower and back.	Water treatment optimization
Water Treatment/ Management	13	Buildout PDWTP molybdenum water treatment plant at reduced capacity to run in conjunction with metals removal system at the PDWTP; influent flow to molybdenum plant varies seasonally in a slip-stream mode and will produce intermediate molybdenum concentration during high-flow periods.	Water treatment optimization
Water Treatment/ Management	14	Use Mayflower TSF as reactor, add chemicals to Tailings Disposal Line near Mayflower TSF. Soluble molybdenum removed during transit to TSF and deposited with tailings in Mayflower TSF.	Treatment alternatives
Water Treatment/ Management	15	All ARD to SDP; modify SDP operations to pH = 10 to remove Mn; SDP to Tenmile; Tenmile to Mill; Mill to Mayflower and back; Mayflower to modified PDWTP which is upgraded for molybdenum removal (pH = 4.5).	Water treatment optimization

Table 3 Initial Options Matrix for Addressing the SBP

Category	Option	Method Summary	Principal SBP Element
Water Treatment/ Management	16	All ARD to SDP; modify SDP operations to pH = 10 to remove Mn; SDP to Tenmile; Tenmile is only source to Mill; Mill to Mayflower; Mayflower to modified PDWTP which is upgraded for molybdenum removal (pH = 4.5).	Water treatment optimization
Water Management	17	Alternative 1 - WQCC Policy 13-1: Consider an alternative location for the discharge water, including a body of water with more assimilative capacity	Water management
Water Treatment/ Management	18	Alternative 2 - WQCC Policy 13-1: Consolidate discharge with another WWTP	Water treatment optimization
Water Treatment/ Management	19	Alternative 3 - WQCC Policy 13-1: Reduce the amount of water discharged	Water management
Water Treatment/ Management	20	Alternative 4 - WQCC Policy 13-1: Consider water recycling measures	Water management
Water Treatment/ Management	21	Alternative 5 - WQCC Policy 13-1: Consider reclaiming water for reuse	Water management
Mine/Mill	22	Alternative 6 - WQCC Policy 13-1: Process change, raw material substitution, or alternatively technology to minimize the source of the pollutant	Source control
Water Treatment/ Management	23	Alternative 7 - WQCC Policy 13-1: Standard treatment methods	Water treatment
Water Treatment/ Management	24	Alternative 8 - WQCC Policy 13-1: Innovative or alternative methods of treatment and advanced treatment, including new designs, stages, components, capacity for treatment plant replacement or upgrade of current plant	Water treatment

Table 3 Initial Options Matrix for Addressing the SBP

Category	Option	Method Summary	Principal SBP Element
Water Treatment/ Management	25	Alternative 9 - WQCC Policy 13-1: Improved operation and maintenance of existing facilities in order to maximize treatment of removal of the pollutant	Water treatment
Water Treatment/ Management	26	Alternative 10 - WQCC Policy 13-1: Seasonal or controlled discharge options to minimize discharging during critical water quality periods	Water management
Water Treatment/ Management	27	Alternative 11 - WQCC Policy 13-1: Watershed trading	Water management
Water Treatment/ Management	28	Alternative 12 - WQCC Policy 13-1: Land application of wastewater	Water management
Water Treatment/ Management	29	Alternative 13 - WQCC Policy 13-1: Total containment of wastewater	Water management
Water Treatment/ Management	30	Alternative 14 - WQCC Policy 13-1: Other alternatives to minimize the effects of the proposed discharge activity	All
Not applicable	31	Alternative 15 - WQCC Policy 13-1: No action	None

The site-water balance model was used to simulate options that require modifications to the existing water management system. Such options would require routing all excess water through the SDP and then directing the effluent to the PDWTP for final water treatment prior to discharge from the site. The limited storage capacity, constraints imposed by water rights obligations, and the highly variable contribution of water from precipitation (mostly from snowmelt) caused some options to not meet the principal criteria, and these were not retained for further analysis. The main criteria each option first had to meet, prior to specific consideration of elements of the SBP, were:

1. The option could be physically implemented
2. Proposed chemical processes must have a high probability of being effective

3. The option must meet the seasonal hydraulic demands of the mine water management system
4. All water requiring treatment for molybdenum and metals would be routed to the appropriate location
5. Tailings storage facility operational requirements (i.e., pond water levels) are met.

Source control measures could include capture of seeps and springs with elevated molybdenum and limiting the quantity of soluble molybdenum introduced to the mill by strategically processing less ore containing oxidized material. In the first instance, Climax already captures known seeps to the maximum extent practicable, so that is not a new action. In the second, the variability of the ore, the limited ability of Climax to change the long-term mine plan, and the physical characteristics of the tailings allows limited adjustment in ore processing to achieve source control for soluble molybdenum during the milling process. Climax has already adjusted the mine plan to delay for as long as possible the processing of ore with a higher oxidized material content. Additionally, Climax evaluated the potential to delay the mining of oxidized ore (Option 2, **Table 3**) either by reconfiguring the mine plan to avoid oxidized material or by stockpiling oxidized material and blending back into the milling process when higher sulfide content ore is available. While either approach (i.e., delay or stockpiling) may address near-term objectives of controlling soluble molybdenum from oxidized ore, neither provides long-term mitigation of molybdenum concentrations associated with partially oxidized ore.

Construction of a new water treatment plant to remove molybdenum is an option. In addition, there are options to reconfigure the two existing water treatment plants to remove molybdenum, along with the other metals already removed, prior to discharge. Several chemical processes are available, and in each case the introduction of new reagents to the site (e.g., ferric sulfate) and the ability to implement the required modification without interrupting the present level of control were considered. Options that involve modification of the existing water treatment plants with no change in the water management system have a reasonable chance of meeting the hydraulic demand criterion because the changes would be implemented in the current system already designed to process peak flows. All options that include active water treatment will require proper bench-scale and pilot testing to advance engineering design, if selected by Climax. For purposes of this evaluation, there is enough existing information from a combination of literature, preliminary testing conducted, and professional judgement, to be able to evaluate water treatment options under the goals and objectives of the SBP.

Stantec applied the criteria listed, considered the operational limitations, and the significant hydraulic demands for site-wide water management to reduce the number of options for further analysis. **Table 4** lists options that were not advanced to the next level of evaluation and provides a summary of the rationale as to why each option was no longer considered. **Table 5** lists the six options (including sub-options) retained for further development. **Appendix A** provides detail regarding application of the criteria, listed previously, for selection of options to both no longer consider or progress in the evaluation. The options matrix presented in **Appendix A** was applied solely to advance a smaller number of options for more detailed consideration. **Table 5** also provides an estimate of the range in concentration of molybdenum that would be expected for each option. The values listed are based on: (1) preliminary testing of the ferric iron adsorption process as referenced in the CH2M Hill (2011) and Golder (2017) reports for Option 9, (2) limited bench-scale testing of the lead chloride option (10b) as reported in **Appendix B** of this report, and (3) professional judgment based on Stantec's water treatment experience and expertise. More definitive projections can only be produced through additional testing and engineering design, which would naturally follow after selecting an option or options to progress to a higher level of engineering design, which is beyond this scope of this work. .

Table 4 Options Eliminated and Rationale

Category	Option	Method Summary	Rationale for Removal from Further Consideration
Mine/Mill	1	Do not mine oxidized ore	• Not mining the oxidized ore would effectively the operation unviable • Oxidized ore is the main ore type for the next several years • Does not address existing molybdenum sources
Mine/Mill	2	Delay mining oxidized ore until molybdenum removal method is in place	• Mine plan has been adjusted to limit processing oxidized ore • Not a stand-alone approach • If oxidized ore is stockpiled, need substantial space for storage • Does not address existing molybdenum sources
Mine/Mill	3	Recover molybdenum at mill and receive credits; metallurgical process	• No effective metallurgical process identified to remove molybdenum from oxidized ore • Time to implement prohibitive • Does not address existing molybdenum sources
Mine/Mill	4	Recover molybdenum at mill and receive credits utilizing resin ion exchange	• Time to implement prohibitive • Does not address existing molybdenum sources
Mine/Mill	5	Dry stack or thicken tailings and treat water	• Time to implement is prohibitive • Physical properties of tailings are not conducive • Does not address existing molybdenum sources
Mine/Mill	6	Install counter current decantation system to recirculate high molybdenum water; discharge tailings with low molybdenum water	• Time to implement is prohibitive • Physical properties of tailings are not conducive • Does not address existing molybdenum sources
Mine/Mill	7	Separate high molybdenum water and use the underground as reactor by combining with 5-Shaft and routing back underground	• Strict limitations on water level in the underground limit potential for use as a reactor • Chemistry of underground is not conducive for molybdenum removal using iron • Separating high molybdenum water at mill limiting • Substituting freshwater for tailings slurry make up impacts water balance • Does not address existing molybdenum sources
Water Treatment/ Management	8	Tailings to Tenmile while oxidized ore is mined; Tenmile pool to Mill and SDP; SDP re-configured to pH = 4.5, SDP effluent directed to PDWTP	• Impending closure of Tenmile TSF precludes this use • Available capacity for tailings is less than total tailings generated under current mine plan • Water balance and hydraulic demand not met
Water Treatment/ Management	15	All ARD to SDP; modify SDP operations to pH = 10 to remove Mn; SDP to Tenmile; Tenmile to Mill; Mill to Mayflower and back; Mayflower to modified PDWTP which is upgraded for molybdenum removal (pH = 4.5)	• A modification of water management plan under Option 12 • Subject to Tenmile TSF closure • Does not meet water balance and hydraulic demand
Water Treatment/ Management	16	All ARD to SDP; modify SDP operations to pH = 10 to remove Mn; SDP to Tenmile; Tenmile is only source to Mill; Mill to Mayflower; Mayflower to modified PDWTP which is upgraded for molybdenum removal (pH = 4.5)	• A modification of water management plan under Option 12 • Subject to Tenmile TSF closure • Does not meet water balance and hydraulic demand

Table 4 Options Eliminated and Rationale

Water Management	17	Alternative 1 - WQCC Policy 13-1: Consider an alternative location for the discharge water, including a body of water with more assimilative capacity	• Neither the Eagle River or Arkansas River has sufficient assimilative capacity • While Dillion Reservoir does have more assimilative capacity, the facility serves as the drinking water supply for metropolitan Denver • Climax has no ownership of Dillion Reservoir and cannot require Denver Water to accept discharge from Climax • Represents a significant impact on existing water rights and would require re-litigating existing water rights agreements
Water Treatment/ Management	18	Alternative 2 - WQCC Policy 13-1: Consolidate discharge with another WWTP	• WWTP with the best potential to accept Climax discharge is Blue River facility with a capacity of 4 MGD; Climax discharge is 7 times larger at peak flow; the systems are incompatible • Even if the Blue River facility could take Climax water, there would be no expected improvement in treated water quality because the Blue River plant is a sewage treatment plant and not designed to treat molybdenum • Blue River WWTP is under no obligation to accept water from Climax
Water Treatment/ Management	19	Alternative 3 - WQCC Policy 13-1: Reduce the amount of water discharged	• A material change in the amount of water discharged would require that much of the Climax mine area be closed, covered, and reclaimed • Unlikely that achieving sufficient reduction in water discharged could be accomplished and maintain active mining operation
Water Treatment/ Management	20	Alternative 4 - WQCC Policy 13-1: Consider water recycling measures	• Recycling water is a key part of the mining operation • Limiting the amount of water brought into the mining operation has been a goal for Climax and the amount diverted into the system has been reduced over the past few years • Additional decrease in water brought in presents risk to the mining operation in that there might not be enough water to run the mill • Other options are available that do not introduce the risk of running out of water
Water Treatment/ Management	21	Alternative 5 - WQCC Policy 13-1: Consider reclaiming water for reuse	• Reclaiming water in the mining operation is already optimized • Limited additional reclaim can be accomplished
Mine/Mill	22	Alternative 6 - WQCC Policy 13-1: Process change, raw material substitution, or alternatively technology to minimize the source of the pollutant	• Alternatives to limit the source of soluble molybdenum are addressed in Options 1 to 6 • Options to change the process are also addressed in Options 1 to 6 as well we Option 19 (i.e., close Tenmile TSF)
Water Treatment/ Management	23	Alternative 7 - WQCC Policy 13-1: Standard treatment methods	• This alternative is addressed in Options 9 to 13
Water Treatment/ Management	24	Alternative 8 - WQCC Policy 13-1: Innovative or alternative methods of treatment and advanced treatment, including new designs, stages, components, capacity for treatment plant replacement or upgrade of current plant	• This alternative is addressed in Options 9 to 13
Water Treatment/ Management	25	Alternative 9 - WQCC Policy 13-1: Improved operation and maintenance of existing facilities in order to maximize treatment of removal of the pollutant	• This alternative is addressed in Options 10 to 16

Table 4 Options Eliminated and Rationale

Water Treatment/ Management	26	Alternative 10 - WQCC Policy 13-1: Seasonal or controlled discharge options to minimize discharging during critical water quality periods	• The PDWTP operation supports water management objectives as Climax by maintaining tailings pond elevations within operational limits by variable seasonal throughput • The range in flows treated (from 14,000 gpm during snowmelt to about 25% of the maximum capacity in late summer) is optimized to meet operation constraints and water rights obligations • No additional improvements are identified
Water Treatment/ Management	27	Alternative 11 - WQCC Policy 13-1: Watershed trading	• On the basis of meeting the water supply use category for protection of human health, this option is not considered to address questions involving protection of human health
Water Treatment/ Management	28	Alternative 12 - WQCC Policy 13-1: Land application of wastewater	• The topography at the Climax mine is not suitable for land application • Soils are thin and discontinuous also limiting the effectiveness of land application • Volume of water to land apply would overwhelm the land application system • Climate not conducive to year-round land application; significant winter conditions
Water Treatment/ Management	29	Alternative 13 - WQCC Policy 13-1: Total containment of wastewater	• Storage volume at Climax is insufficient to store the volume of a full year of snowmelt • Additional volume is not feasible • Water rights obligations preclude this option
Water Treatment/ Management	30	Alternative 14 - WQCC Policy 13-1: Other alternatives to minimize the effects of the proposed discharge activity	• Options 1 to 16 are a comprehensive list of methods that might be implemented to reduce the concentration of molybdenum in discharge at Climax • Closing the mine is another alternative; however, the economic ramifications at the local, regional, and international level are considered significant • Even if the mine closed, soluble molybdenum will be discharged from Climax
Not applicable	31	Alternative 15 - WQCC Policy 13-1: No action	• Molybdenum concentrations are expected to increase above current conditions when oxidized ore is mined

Table 5 Final Set of Options for Further Analysis and Consideration

Category	Option	Method Summary	Projected Molybdenum Concentration (µg/L)++
Water Treatment	9	Build molybdenum removal plant based on current 30% design (CH2M Hill)	200 to 500
Water Treatment	10a	SDP pH = 10 for Mn removal; PDWTP Reactor 1 at pH 8-10 for metals removal; PDWTP Reactor 2 at pH 4.5 to 5 for molybdenum removal; clarifiers at pH 4.5-5	200 to 500
Water Treatment	10b	SDP as is; PDWTP Reactor 1 with pH adjusted for optimum removal of molybdenum with $PbCl_2$; PDWTP Reactor 2 at pH 10 for residual Pb and metals	500 to 5,000
Water Treatment/Management	11	SDP at 4.5 for molybdenum removal; PDWTP at pH 10 for metals removal	500 to 1000
Water Treatment/Management	12	SDP at 10 for metals removal; PDWTP at pH 4.5 for molybdenum removal	200 to 500
Water Treatment	13	Buildout PDWTP molybdenum water treatment plant at reduced capacity to run in conjunction with metals removal system at the PDWTP; influent flow to molybdenum plant varies seasonally in a slip-stream mode and will produce intermediate molybdenum concentration during high-flow periods.	1,000 to 5,000
Water Treatment/Management	14	Add reagents to the Tailings Disposal Line near Mayflower TSF to reduce the concentration of soluble Mo prior to deposition of tailings at Mayflower TSF	5,000 to 10,000

++ projected concentration ranges may change as additional information becomes available

3.4 SUMMARY OF RETAINED OPTIONS

3.4.1 Option 9 – Build Molybdenum Treatment Plant

Plans and prefeasibility-level design of a molybdenum treatment plant were first completed in 2011 (CH2M Hill), and a review of the design was conducted by Golder in 2017. The molybdenum treatment plant would be built adjacent to the PDWTP such that the two systems could be plumbed together. Molybdenum removal is by adsorption to iron oxyhydroxide through addition of ferric sulfate ($Fe_2[SO_4]_3$) with the pH adjusted to 4.5 using sulfuric acid (H_2SO_4). The system would be operated to produce high-density sludge, which optimizes the footprint of the planned on-site solids disposal facility. Previous estimates of capital cost and operations and maintenance for this option are provided in **Table 6.**

Table 6 Summary of Cost Estimates for Building, Operating, and Maintaining a Molybdenum Water Treatment Plant

Source	Capital Cost	Operations and Maintenance (yearly)
CH2M Hill, 2011	\$63,089,379	\$2,597,000
Golder, 2017	\$79,652,000^{+}	\$2,829,000$^{(1)}$

Note: (1) values listed are escalated 2019 costs from the Golder report

Regarding the SBP, Option 9 addresses the following:

- **Potential treatment alternatives**: molybdenum would be removed at a new facility adjacent and connected to the PDWTP, all other water treatment operation would remain the same (i.e., as currently implemented)
- **Treatment optimization**: the addition of the molybdenum treatment plant would provide management of constituents in water discharging from Climax
- **Expected effluent quantity**: under normal conditions, the maximum flow from the system is 14,000 gpm, which is the maximum hydraulic capacity of the PDWTP and would be the maximum hydraulic capacity of a new molybdenum treatment plant
- **Expected effluent quality**: based on current level of testing, effluent concentrations of molybdenum would range from 200 to 500 µg/L, subject to the influent concentration of molybdenum.

Finally, Option 9 would not require any changes in the current water management system operation, which means the option would satisfy operational requirements for the TSFs.

3.4.2 Option 10a/b – Modify Existing Water Treatment Facilities with no Change in Water Management

3.4.2.1 Option 10a – Metals in PDWTP Reactor 1 and Molybdenum Removal in PDWTP Reactor 2

There is potential that the existing water treatment infrastructure can be modified to also remove molybdenum. In this option, the SDP would be operated at pH 10 for removal of metals. The adjustment of operating pH at SDP would require no infrastructure changes, only the rate of lime dosing to the reactors. At the PDWTP, Reactor 1 would be operated at pH 8, depending on the pH of water from the Mayflower TSF, for removal of any residual metals in the influent feed flow to the PDWTP. Reactor 2 would be operated for removal of molybdenum by adjusting the pH to 4.5 to 5 with addition of sulfuric acid, and adsorption of molybdenum to ferric oxyhydroxide formed by addition of ferric sulfate. Additionally, a chemical oxidant (e.g., potassium permanganate [$KMnO_4$]) would be added to Reactor 2 to remove any residual manganese.

A portion of the PDWTP facility would need to be upgraded to provide resistance to low pH conditions because the PDWTP is constructed of low-carbon steel that is not suitable for handling acidic pH conditions. Due to the extent of changes required for implementation of Option 10a, careful planning would be required because of the need for essentially continuous discharge at Climax.

One potential concern with Option 10a is whether the system maximum capacity (14,000 gpm) would need to be de-rated for the different solids composition produced in the process. The concern originates from the PDWTP design criteria that required the clarifier to be 160 feet in diameter to effectively separate the ferric iron solids. The PDWTP has clarifiers that are 140 feet in diameter and may not be sufficiently effective for a 14,000-gpm throughput with the amount of iron required for molybdenum removal. Testing is required to establish the solids settling characteristics from the combined chemical oxidation and ferric co-precipitation process to ensure that an optimized PDWTP process for molybdenum removal will not result in a bottleneck in the water management system during spring snowmelt.

The following details for implementation of this option would be needed to advance the process in engineering design:

- Verify that treatment sequence will not remobilize constituents between Reactor 1 and Reactor 2
- Bench-scale testing of the process chemistry is conducted to verify constituent removal and solids settling characteristics
- Determine extent and impact of plant capacity reduction on site-wide water balance
- Validate SDP capacity will not be de-rated with additional sludge production at higher pH

Regarding the SBP, Option 10a addresses the following:

- **Influent control measures**: by routing flows to the SDP and PDWTP and modifying the plant operations the feed water quality would be controlled
- **Potential treatment alternatives**: SDP would be modified to operate at pH 10 to remove metals, followed by molybdenum at the PDWTP, with the capability to remove residual metals in Reactor 1 at the PDWTP
- **Treatment optimization**: the suggested modifications and set point for pH would optimize removal of constituents at both water treatment plants
- **Expected effluent quantity**: under normal conditions, the maximum flow from the system is 14,000 gpm, which is the maximum hydraulic capacity of the PDWTP
- **Expected effluent quality**: the chemical treatments proposed under Option 10a are the same as currently used and as proposed under Option 9 (the molybdenum water treatment plant); therefore, expected range in effluent concentrations of molybdenum is 200 to 500 µg/L, subject to the influent concentration of molybdenum.

3.4.2.2 Option 10b – Metals and Molybdenum in PDWTP Reactors 1 and 2

Like Option 10a, this option modifies the existing water treatment facilities with no changes to the water management system. The SDP would be operated at pH 7, which is consistent with current operations. The SDP effluent would either be discharged to Tenmile TSF and then routed to Mayflower TSF as needed or discharge directly to Mayflower TSF when Tenmile TSF is no longer available. Mayflower TSF would remain the main source of feed water to the PDWTP. In the PDWTP, Reactor 1 would be operated at pH around 7 with addition of lead chloride ($PbCl_2$) for precipitation of molybdenum. Reactor 2 would be operated at pH 10 (equal to current conditions) to precipitate residual metals. Sodium hydrosulfide (NaHS), or a suitable substitute, would also be added to Reactor 2, if needed, to remove any residual lead. The use of reagents containing lead or sulfide would require careful safety and residual water quality considerations. Additional process components would be needed at the PDWTP for dosing of reagents.

The following details for implementation of this option would be needed to advance the process in engineering design:

- Bench-scale testing of the process chemistry is conducted to verify constituent removal
- Determine extent and impact of plant capacity reduction on site-wide water balance
- Determine long-term potential for leaching of lead from stored sludge.

Regarding the SBP, Option 10b addresses the following:

- **Influent control measures**: by routing flows to the SDP and PDWTP and modifying the plant operations the feed water quality would be controlled.
- **Potential treatment alternatives**: Some changes to the operation of both the SDP or PDWTP. Additional process components to support formation of insoluble lead molybdate and to remove residual lead would be required.
- **Treatment optimization**: the suggested modifications and set point for pH would optimize removal of constituents at both water treatment plants.
- **Expected effluent quantity**: under normal conditions, the maximum flow from the system is 14,000 gpm, which is the maximum hydraulic capacity of the PDWTP.
- **Expected effluent quality**: the expected effluent concentrations of molybdenum range from 500 to 5,000 µg/L based on preliminary test data, subject to the influent concentration of molybdenum.

3.4.3 Option 11 – Molybdenum Removal at SDP, Metals Removal at PDWTP, Re-route Flows

In this option, all site water requiring molybdenum treatment is routed to the SDP, which is modified to operate at a pH of 4.5 with molybdenum removal by adsorption to iron oxyhydroxide. While there will be some removal of iron and possibly aluminum, all other metals will be removed at the PDWTP, which will operate as currently. To route flows as intended, the current water management system would require modification. Because of the need to change the water management system to implement this option, the main criterion of evaluation is a test of whether the hydraulic demands associated with the annual hydrologic cycle can be met. The site-wide water balance model was modified to re-route flows. The model was used to evaluate if the hydraulic demand could be accommodated in the modified system. **Table 7** lists the major changes in water routing associated with this option as compared to current operations.

Option 11 was simulated in the site-wide water balance model by enacting the following changes:

1. Disable PDWTP feed from Mayflower pond
2. PDWTP feed is provided from Tenmile via a new connection between these elements
3. Mayflower pond can send excess process water to the SDP via a new connection between these elements whenever the SDP has excess treatment capacity
4. Routine transfer of process water from Tenmile to Robinson Lake is disabled so that low-molybdenum water in Tenmile is sent to the PDWTP and not used as reclaim
5. When required by low water levels in Mayflower, Tenmile stops supplying feed to the PDWTP and supplies makeup water to Mayflower instead.

Table 7 Comparison of Water Routing Under Current Conditions and Option 11

Component	Current Operations	Option 11
Mill Reclaim Source:	Mayflower (1st) or Tenmile (2nd) via Robinson Lake	Mayflower (exclusively) via Robinson Lake
Mill Slurry Destination:	Mayflower	Mayflower
Primary Tenmile Outflows:	Robinson Lake, Mayflower	PDWTP, Mayflower (when makeup needed)
Primary Mayflower Outflows:	Robinson Lake, PDWTP	Robinson Lake, SDP
SDP Function:	Solids, iron, aluminum, and manganese removal	Molybdenum removal via operation at pH = 4.5
SDP Feed:	All ARD to SDP	All ARD to SDP + Mayflower decant (as SDP capacity allows)
SDP Effluent Destination:	Tenmile	Tenmile
PDWTP Function:	Manganese removal via operation at pH = 10	Manganese removal via operation at pH = 10
PDWTP Feed:	Mayflower	Tenmile
PDWTP Effluent Destination:	Tenmile Creek	Tenmile Creek

Note: shaded cells reflect a change in flow

The transfer of water from Tenmile to the PDWTP is based on the original model configuration calculation of the amount of surplus water in Tenmile that should be sent to Mayflower. This calculation considers several factors such as the current Tenmile pool elevation compared to reference levels, snowpack melting, and releases required to meet water rights obligations. Rather than sending the calculated surplus water to Mayflower as in the current configuration, under Option 11 the surplus water is sent to the PDWTP for treatment and discharge to Tenmile Creek. The rate that surplus water is sent from Tenmile to the PDWTP is limited to the PDWTP maximum feed rate of 14,000 gpm. The normal flow of excess water from Tenmile to the PDWTP under this option is stopped when Mayflower is at risk of not having enough water to meet the process water demand. Under this condition, water in Tenmile is sent to Mayflower; however, in actual operation when supplying reclaim, Tenmile water would likely be sent directly to Robinson Lake rather than to Mayflower. In the current operational configuration, Mayflower receives all surplus water from Tenmile and excess water in Mayflower is controlled through managed releases from Mayflower to the PDWTP. As a result, Mayflower does not typically experience lower water volumes. Under Option 11 with much of the surplus water in Tenmile sent to the PDWTP, water levels in Mayflower tend to fluctuate more over the course of the simulation and Mayflower requires periodic supplementation through transfers from Tenmile (**Figure 2**).

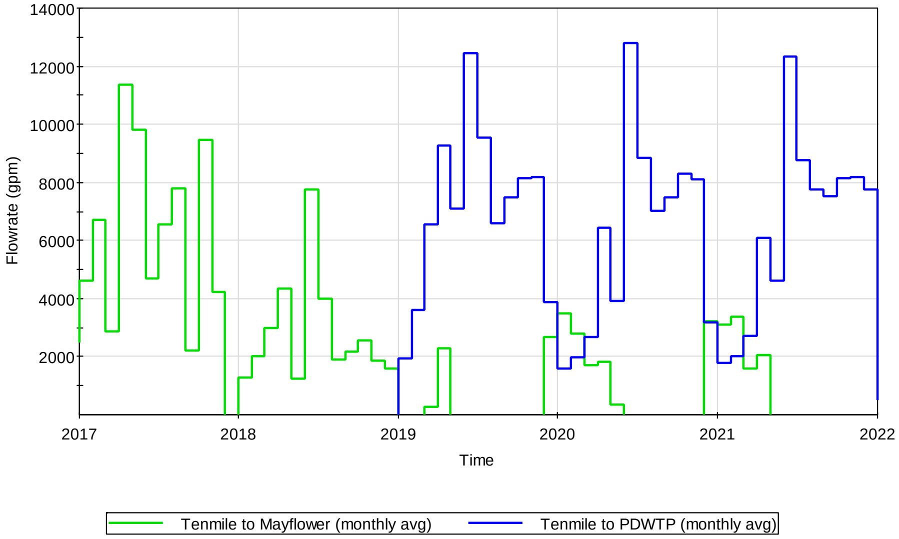

Figure 2 Average Monthly Outflows from Tenmile to Mayflower and to the PDWTP (2017 to 2018 current configuration; 2019 to 2022 Option 11)

Under Option 11, Mayflower periodically has water inflows that exceed reclaim demands and loss to voids. If current flows to the SDP are less than the simulated SDP intake rate (6,900 gpm), excess Mayflower water is sent to SDP for treatment of molybdenum. The rate of transfer of excess water from Mayflower to SDP is calculated as the difference between the maximum SDP capacity and the sum of all other SDP inflows. **Figure 3** shows the capacity of SDP beyond what is needed for treatment of existing flows and flow from Mayflower to the SDP. Mayflower pool elevation is also shown to illustrate periods of high pool elevation and low SDP capacity.

The feasibility of Option 11 was evaluated based on the ability to manage water levels in Tenmile and Mayflower assuming an average annual precipitation regime and on the ability to provide reclaim water as needed. Reclaim water demands continued to be met under Option 11 through transfers of water from Tenmile to Mayflower. Water levels in Tenmile and Mayflower (**Figure 4**) were for the most part managed within the operational limits, but both pools experienced greater variability in pool elevations and periods where both pools were at or slightly exceeded the operational limits established for TSF operations. The primary reasons for this appear to be constraints on the ability to send water from Mayflower to SDP (due to the limitation of SDP maximum feed rate), coupled with storage limitations in Tenmile as it supplies feed to the PDWTP. Given the operational conditions for the TSFs (e.g., high water level limit), simulated periods when the predicted TSF water level exceeds the operational limit indicate the option is not viable. Because the predicted high-water level periodically exceeds the established limit under the favorable conditions simulated (i.e., average precipitation and maximum design flow at SDP), Option 11 is not viable for implementation at Climax.

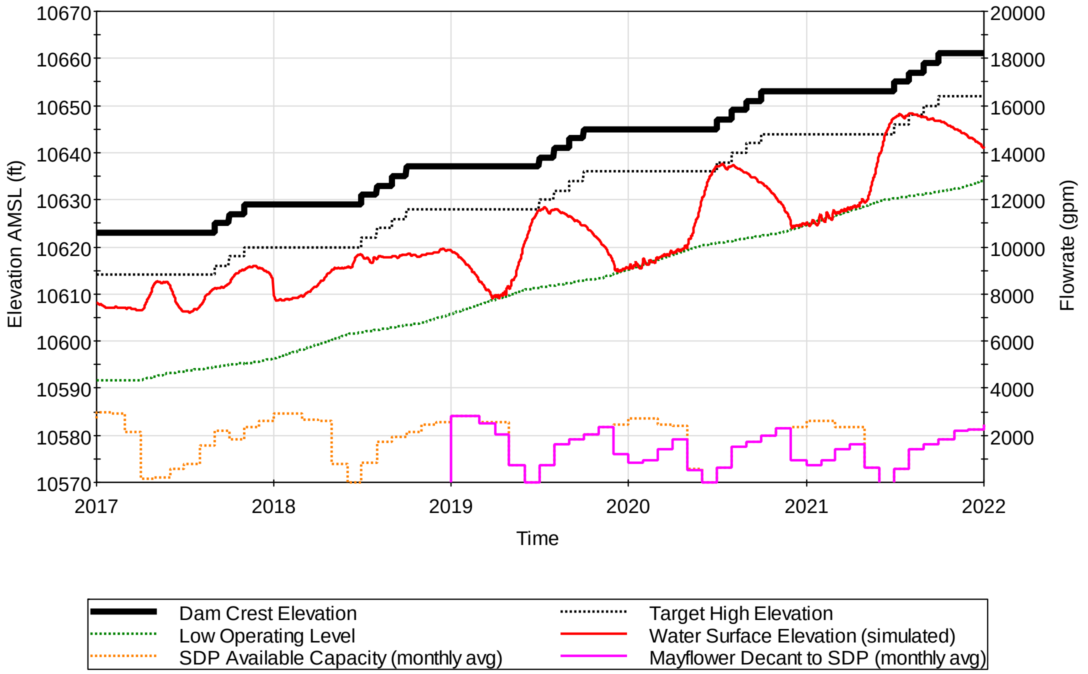

Figure 3 Simulated Average Monthly Flow from Mayflower TSF to the SDP Compared to Mayflower Pool Elevations under Option 11

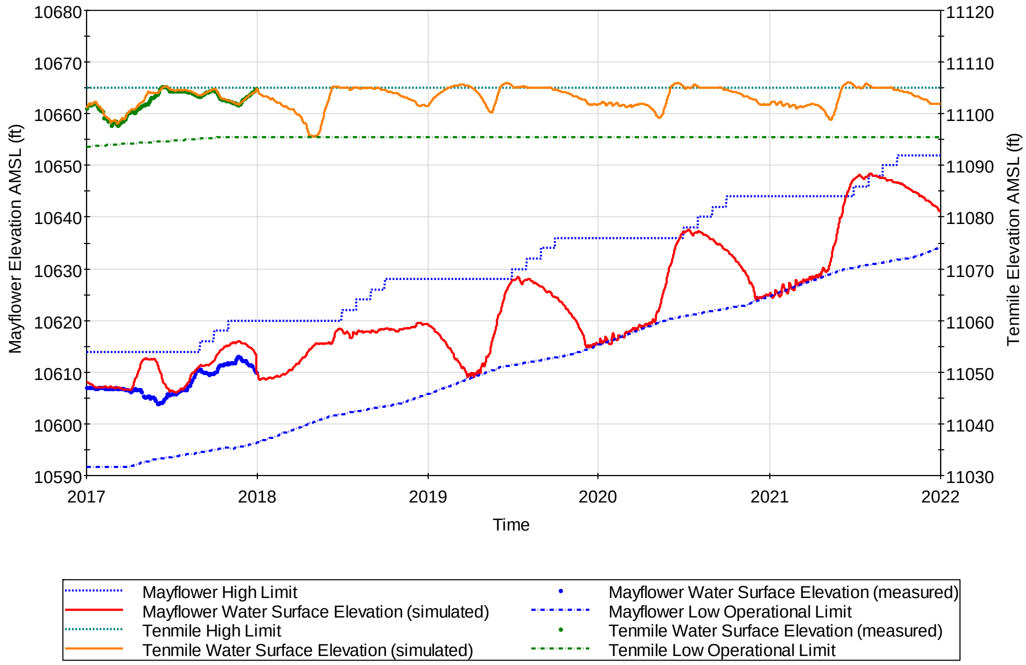

Figure 4 Simulated Pool Elevations Under Option 11

Regarding the SBP, Option 11 addresses the following:

- **Influent control measures**: by routing flows to the SDP and PDWTP and modifying the plant operations the feed water quality is controlled
- **Potential treatment alternatives**: SDP is modified to operate at pH 4.5 to remove molybdenum, followed by removal of metals, including manganese, at the PDWTP
- **Treatment optimization**: each treatment plant will be a single process facility optimized for maximum removal of constituents
- **Water management alternatives**: provides an alternative approach to water management that essentially spreads discharge of the water volume generated during snowmelt over the annual hydrologic cycle while maintaining water supply needs, maintaining tailings impoundments within normal operating conditions, and meeting water rights obligations
- **Expected effluent quantity**: under normal conditions, the maximum flow from the system is 14,000 gpm, which is the maximum hydraulic capacity of the PDWTP. Under Option 11 the simulated annual maximum flow is about 13,000 gpm
- **Expected effluent quality**: the chemical treatments proposed under Option 11 are the same as currently used and as proposed under Option 9 (the molybdenum water treatment plant); therefore, expected effluent concentrations of molybdenum range from 500 to 1,000 µg/L based on preliminary test data, subject to the influent concentration of molybdenum.

Regarding operational limitations for TSFs and flow limitations:

- **Tailings facility operations**: the analysis completed to evaluate Option 11 used average climatic conditions, which are not the same as the design hydrologic condition used to size the PDWTP. Based on the predicted water levels in the TSFs, additional analysis using a hydrologic condition that required management of a larger annual volume of water would likely fail to meet the operational water levels established for the TSFs
- **Flow limits**: while the engineering design flow of the SDP is 6,000 gpm, the actual flow limit is closer to 5,000 gpm. If the analysis is conducted using the reduced operational flow limit at the SDP, Option 11 would not meet the TSF water level requirements for TSF operations.

Because Option 11 does not clearly meet the TSF operational requirements, the probability of being able to implement Option 11 without additional major changes in the facility layout (e.g., additional storage volume or re-building the SDP) is small. Thus, Option 11 will not be evaluated in the cost evaluation process.

3.4.4 Option 12 – Metals Removal at SDP, Molybdenum Removal at PDWTP, Re-route Flows

In this option, all site water requiring metals treatment is routed to the SDP, which is modified to operate at pH 10. Molybdenum will be removed at the PDWTP, which will be modified to operate at pH 4.5. To route flows as intended, the current water management system would require modification. Because of the need to change the water management system to implement this option, the main criterion of evaluation is a test of whether the hydraulic demands associated with the annual hydrologic cycle can be met. The site-wide water balance model was modified to re-route flows and then the model was used to evaluate if the hydraulic demand could be accommodated in the modified system. **Table 8** lists the major changes in water routing associated with this option as compared to current operations.

Table 8 Comparison of Water Routing Under Current Conditions and Option 12

Component	Current Operations	Option 12
Mill Reclaim Source:	Mayflower (1st) or Tenmile (2nd) via Robinson Lake	Mayflower (1st) or Tenmile (2nd) via Robinson Lake
Mill Slurry Destination:	Mayflower	Mayflower
Primary Tenmile Outflows:	Robinson Lake, Mayflower	Robinson Lake, Mayflower
Primary Mayflower Outflows:	Robinson Lake, PDWTP	Robinson Lake, SDP
SDP Function:	Solids, iron, aluminum, manganese removal	Manganese removal via operation at pH = 10
SDP Feed:	All ARD to SDP	All ARD to SDP + Mayflower decant (as SDP capacity allows)
SDP Effluent Destination:	Tenmile	PDWTP
PDWTP Function:	Manganese removal via operation at pH = 10	Molybdenum removal via operation at pH = 4.5
PDWTP Feed:	Mayflower	SDP Effluent
PDWTP Effluent Destination:	Tenmile Creek	Tenmile Creek

Option 12 was implemented in the water balance model by enacting the following changes:

1. Disable PDWTP feed from Mayflower pond (as with Option 11)
2. SDP effluent to Tenmile pond is disabled (SDP overflows continue to go to Tenmile)
3. PDWTP feed is provided from SDP effluent via a new connection
4. Mayflower pond can send water excess process water to the SDP via a new connection between these elements whenever the SDP has excess treatment capacity (as with Option 11)
5. When required by low water levels in Mayflower, Tenmile can supply makeup water to Mayflower if Tenmile remains at or above its minimum operational limit.

Under Option 12, the SDP becomes the source of feed to the PDWTP. As a result, the maximum feed rate to the PDWTP is reduced from the current 14,000 gpm to the simulated SDP maximum rate of 6,900 gpm. Because of this reduction in capacity, the removal of excess water from the mine’s hydrologic system via treatment and discharge to Tenmile Creek will occur at a more constant rate and over a longer time period annually than has occurred historically. This simulated change in PDWTP operations beginning in 2019 is illustrated in **Figure 5**. Furthermore, operating the PDWTP in this manner would necessitate a greater reliance upon careful management of storage volume within the system to both store high inflows during spring runoff and to supply adequate process water in late winter and early spring when inflow rates are minimal.

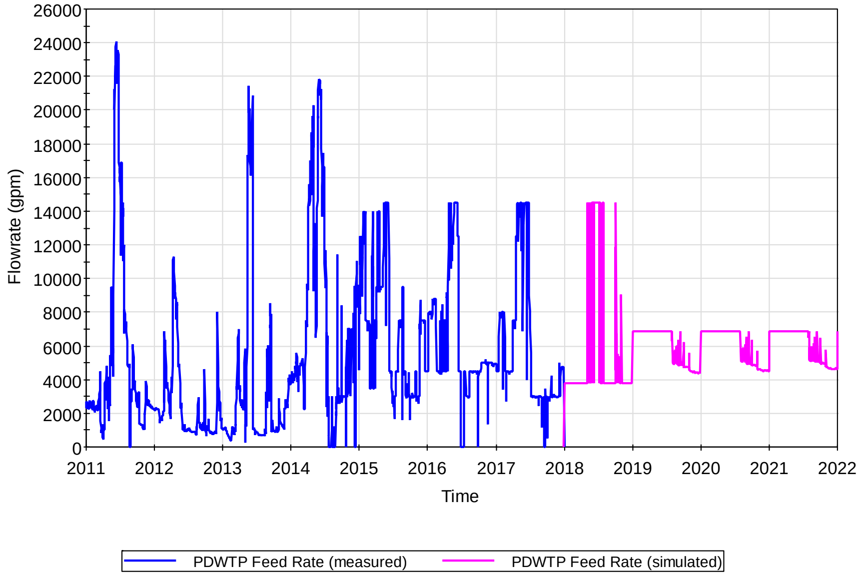

Figure 5 Measured and Simulated Future PDWTP Feed Rate with Option 12 Beginning in 2019

Option 12 provides the ability for routing of water in Mayflower to the SDP if the SDP feed rate is less than the maximum SDP capacity. By adding flow routing from Mayflower to SDP, more excess water can be delivered out of the system via the SDP than would occur by relying solely on existing flows to the SDP. Under Option 12, flow from Mayflower to the SDP must not occur from the beginning of August through the end of December to allow Mayflower to build storage volume for use in early spring when Mayflower losses exceed inflows. Water volumes in Mayflower and Tenmile are quickly replenished during the spring snowmelt. **Figure 6** shows monthly average SDP capacity and monthly average Mayflower flow to the SDP. Mayflower pool elevation is also included to illustrate the relationship between allowed flow from Mayflower to the SDP and Mayflower pool levels (**Figure 6**).

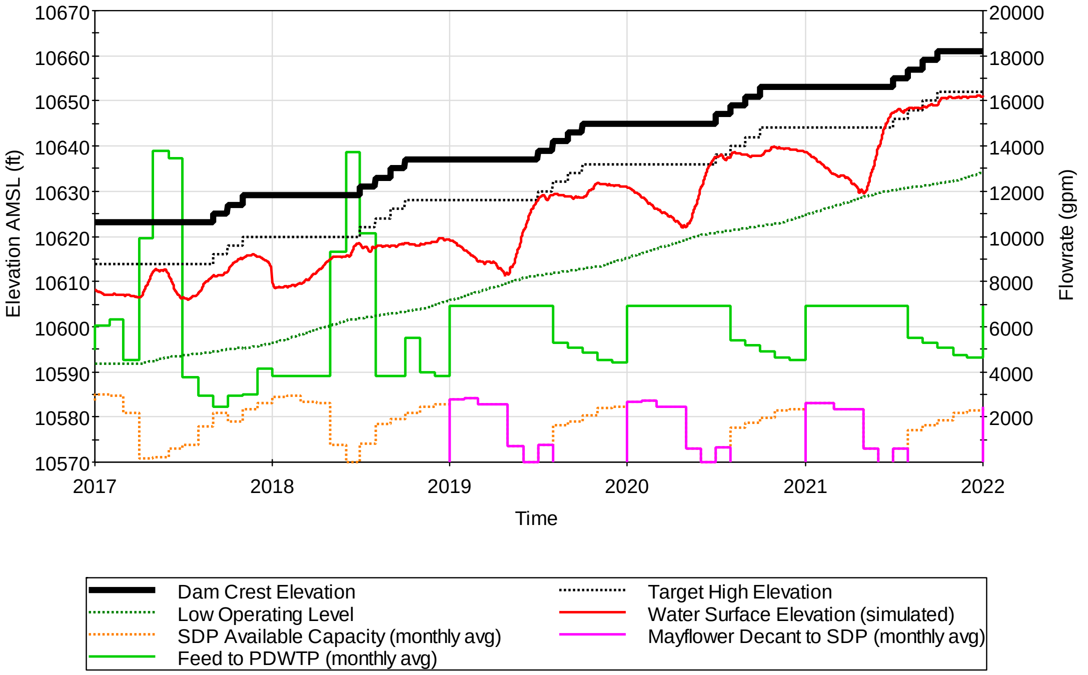

Figure 6 **Simulated Monthly Average Flow from Mayflower to the SDP Compared to Mayflower Pool Elevations Under Option 12**

As is currently the case, flows to SDP that exceed the SDP treatment capacity would bypass the SDP and continue into Tenmile TSF. However, with SDP effluent being routed to PDWTP under Option 12 rather than to Tenmile, inflow rates to Tenmile (and subsequently outflow rates) would be significantly reduced. In the current configuration, any surplus water in Tenmile is decanted to Mayflower (provided Mayflower has storage capacity), but water levels in Tenmile are generally maintained in the upper region of the operational storage band. Under Option 12, the entire operational storage volume of Tenmile might be periodically required to supplement process water to Mayflower. The Tenmile to Mayflower connection was found to be especially critical during the late winter/early spring period when inflows to the system are limited.

Option 12 was evaluated based on the ability to manage excess water levels in Tenmile and Mayflower assuming an average annual precipitation regime and on the ability to provide reclaim water as needed. Reclaim water demands are met under Option 12 through careful management of water storage in both tailings pools and through large transfers of water from Tenmile to Mayflower. Both pools experienced increased variability in pool elevations and periods where both pools were at or slightly exceeded either the upper or lower operational limits (**Figure 7**). These results suggest that Option 12 is potentially feasible, but under the modeled management and climate assumptions the storage volume is barely adequate. Future climate scenarios with less annual precipitation might impact the availability of reclaim water in late winter, while greater annual precipitation could result in unacceptable pool elevations. The controlling factor for Option 12 is the limitation on feed to the PDWTP which results in the need to continue to operate the PDWTP earlier and later than the current peak periods. Additionally, water would need to be stored on the TSF while waiting for available treatment capacity.

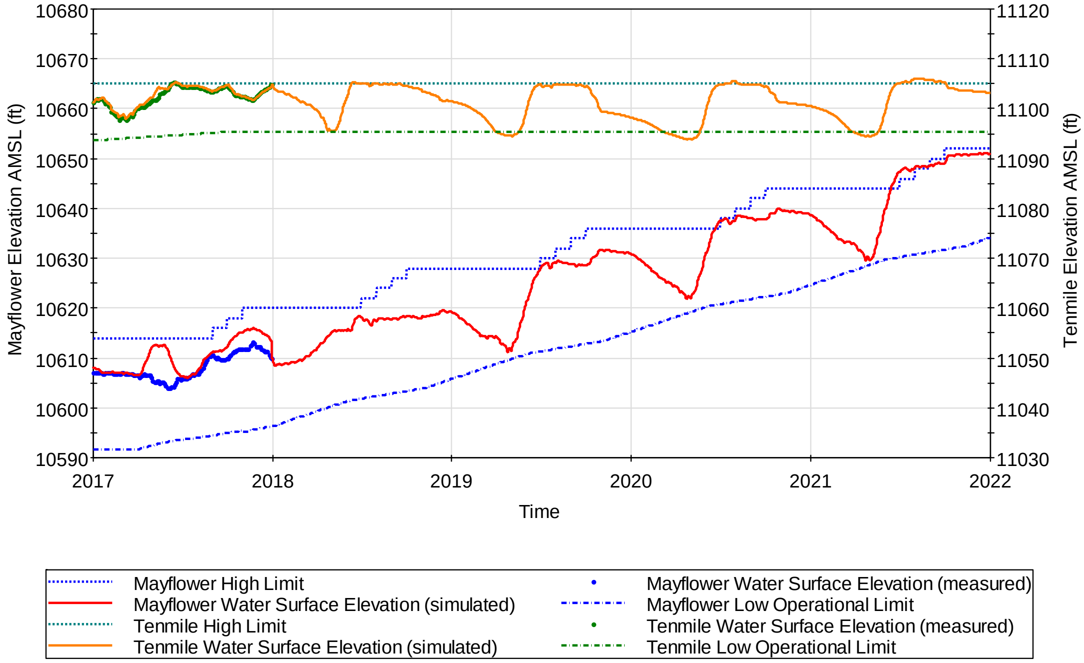

Figure 7 Simulated Tailings Pool Elevations Under Option 12

Regarding the SBP, Option 12 addresses the following:

- **Influent control measures**: by routing flows to the SDP and PDWTP and modifying plant operations, the feed water quality is controlled
- **Potential treatment alternatives**: SDP is modified to operate at pH 10 to remove metals, including manganese, followed by removal of molybdenum at the PDWTP
- **Treatment optimization**: each treatment plant will be a single process facility optimized for maximum removal of constituents
- **Water management alternatives**: provides an alternative approach to water management that essentially spreads discharge of the water volume generated during snowmelt over the annual hydrologic cycle while maintaining water supply needs, maintaining tailings impoundments within normal operating conditions, and meeting water rights obligations
- **Expected effluent quantity**: under normal conditions, the maximum flow from the system is 14,000 gpm, which is the maximum hydraulic capacity of the PDWTP. Under Option 12 the predicted annual maximum flow is approximately 6,900 gpm
- **Expected effluent quality**: the chemical treatments proposed under Option 12 are the same as currently used and as proposed under Option 1 (the molybdenum water treatment plant); therefore, expected effluent concentrations of molybdenum range from 200 to 500 µg/L based on preliminary test data, subject to the influent concentration of molybdenum.

Regarding operational limitations for TSFs and flow limitations:

- **Tailings facility operations**: the analysis completed to evaluate Option 12 used average climatic conditions, which are not the same as the design hydrologic condition used to size the PDWTP. Based on the predicted water levels in the TSFs, additional analysis using a hydrologic condition that required management of a larger annual volume of water would likely fail to meet the operational water levels needed to maintain safe operation of the TSFs
- **Flow limits**: while the engineering design flow of the SDP is 6,000 gpm, the actual flow limit is closer to 5,000 gpm. If the analysis is conducted using the reduced operational flow limit at the SDP, Option 12 would not meet operational water levels in the TSFs.

Because Option 12 does not clearly meet the TSF operational requirements, the probability of being able to implement Option 12 without additional major changes in the facility layout (e.g., additional storage space or re-building the SDP) is small. Thus, Option 12 will not be evaluated in the cost evaluation process.

3.4.5 Summary of Options 11 and 12

Design of the PDWTP was based on a wet-year event that approximates a 1 in 100-year snowmelt event to limit the risk that the facility might not be able to manage snowmelt flows. Combined with the fact that the actual operating maximum flow SDP is about 5,000 gpm indicates more definitively that Options 11 and 12 are not viable. To demonstrate the extent to which Options 11 and 12 fail to meet TSF operational requirements and the hydraulic demand of the water management system, the site-wide water balance model was modified to introduce one wet-year snowmelt event and reduced the flow at SDP to 5,000 gpm. **Figure 8** shows the effects on water levels in the TSFs under the conditions described for Option 11. A similar response of shown under the Option 12 configuration (**Figure 9**). Model results show that the maximum operating water levels are exceeded for sustained periods of time each year, demonstrating more conclusively that Options 11 and 12 are not viable for Climax.

Consideration was also given to the possibility of adding storage where excess water could be routed seasonally to keep the water levels in the TSFs within the operating range. An important distinction related any consideration of adding storage capacity to temporarily handle excess water is that the excess water is **process** water not fresh water, which also influences the characteristics of any additional storage facility (i.e., probably would need to be lined).

Water temporarily stored would then be fed back into the system so that no net water would be stored annually. For design purposes, the Option 11 water balance results were evaluated assuming the design snowmelt, previously described, occurred and that the maximum through put of the SDP remains 5,000 gpm. Under this scenario, Climax would need to provide approximately 1,520 ac-ft of additional storage space to accommodate excess water from the design event snowmelt. Furthermore, the SDP would need to run at full capacity throughout the year in order to process all excess water each year.

Identifying the excess volume is relatively straight forward, finding space for the additional volume is more challenging. Climax operates under a mine permit from the Colorado Division of Mining, Reclamation, and Safety (DRMS), and the mine permit boundary determines the limits of land disturbance under the mining permit. Additional storage of water would also be subject to all water rights obligations in terms of timing and quantity of water delivered. The facility would have to be constructed to store process water, not fresh water, which would increase the cost of a storage facility. Finally, identifying a location where the additional storage volume could reside will require a significant, multi-year effort to develop storage options. All told, while adding storage volume could make either Option 11 or 12 work, the time required to implement is not viable.

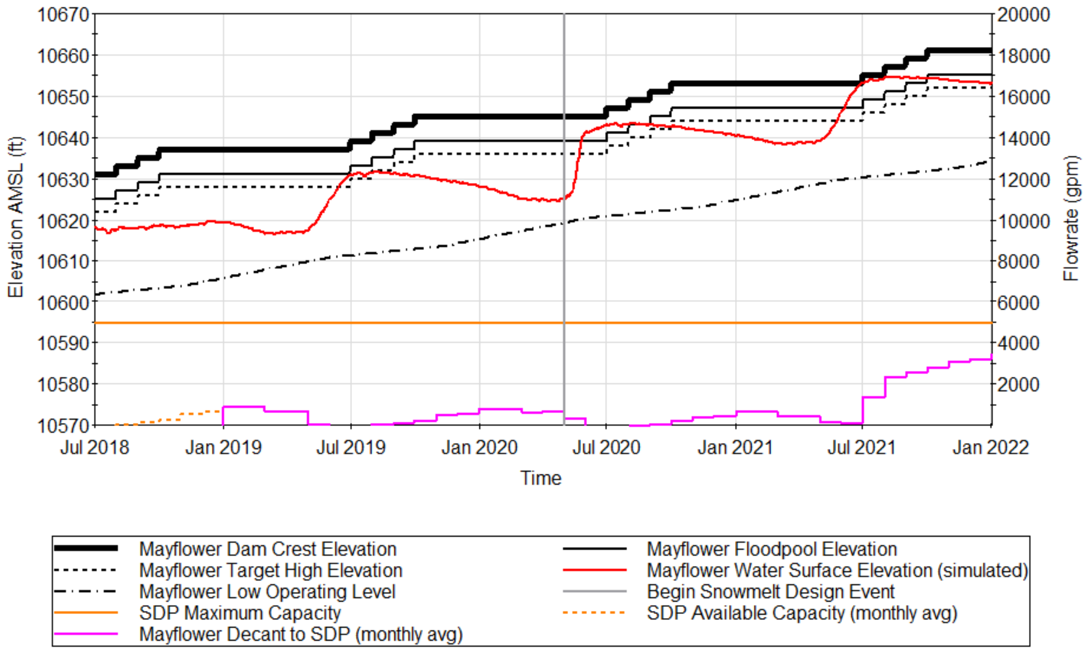

Figure 8 Simulated Tailings Pool Elevations Under Option 11 with a Wet-Year Snowmelt Event in 2020

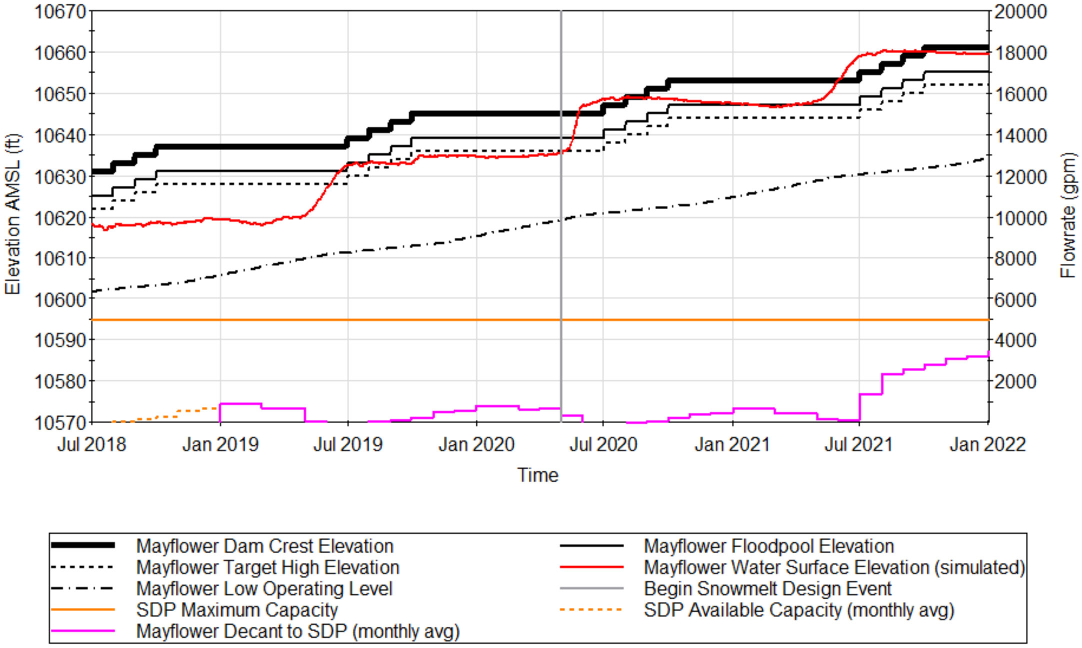

Figure 9 Simulated Tailings Pool Elevations Under Option 12 with a Wet-Year Snowmelt Event in 2020

3.4.6 Option 13 – Build Reduced Flow Molybdenum Treatment Plant and Blend Flows

Option 13 is like Option 9 in that a separate molybdenum water treatment plant would be built based on ferric iron co-precipitation. However, the molybdenum water treatment plant capacity would be less than the full buildout system for Option 9. For purposes of this discussion, two molybdenum water treatment plant capacities will be considered under Option 13: (1) a 3,500 gpm facility (25 percent capacity) and (2) a 7,000 gpm facility (50 percent capacity). However, a similar logic holds for any chosen treatment plant capacity. The reduced capacity molybdenum removal plants would perform in tandem with the PDWTP metals removal plant, reducing molybdenum in the entire process stream during lower flow periods of the year, then processing a portion of the process stream (split-stream operation) during high flow periods of the year. The split-stream operation would treat approximately 25 (or 50) percent of the total flow processed in the PDWTP when operating at full capacity. The split-stream approach assumes effluents from both plants are blended and discharged to Tenmile Creek as a single flow.

For this analysis, Stantec assumed that the concentration of molybdenum in Mayflower Pond would be reduced by one half during spring snowmelt and both the metals and molybdenum removal plants would operate at full capacity. Under these assumptions, the discharged molybdenum from the 25 percent capacity plant during the brief high-flow season could be approximately 35 to 40 percent of typical Mayflower Pond concentrations. Similarly, molybdenum discharged from the 50 percent capacity plant during the brief high-flow season would be approximately 20 to 30 percent of typical Mayflower Pond concentrations. The actual molybdenum concentration achieved would require additional analysis to account for the normal water management program that includes lowering the water level in Mayflower TSF prior to initiation of snowmelt, but also the effects of ore processing.

Molybdenum removal would be maximized (i.e., like concentrations projected for Option 9) during most of the year when the plant (3,500 or 7,000 gpm) is processing most or all discharge flow. An incremental reduction in the discharge concentration of molybdenum would be achieved with the split-stream operation during the high-flow period in spring.

Regarding the SBP, Option 13 addresses the following:

- **Potential treatment alternatives**: molybdenum is removed at a new facility adjacent and connected to the PDWTP, all other water treatment operations would remain the same as currently implemented
- **Treatment optimization**: the addition of the molybdenum treatment plant would provide management of constituents in water discharging from Climax
- **Blending**: with a split-stream operation, the water treatment system would be capable of meeting water quality target values by blending treated waters from the split-stream
- **Expected effluent quantity**: under normal conditions, the maximum flow from the system is 14,000 gpm, which is the maximum hydraulic capacity of the PDWTP
- **Expected effluent quality**: based on current level of testing and the capacity of the molybdenum treatment plant, projected effluent concentrations of molybdenum range from 1,000 to 5,000 µg/L during high flow periods and 200 to 500 µg/L during low flow period, subject to the influent concentration of molybdenum.

Finally, Option 13 does not require any changes in the current water management system operation, which means the option satisfies operational requirements for the TSFs.

3.4.7 Option 14 – Removal of Molybdenum from Tailings Stream

Option 14 is an extension of the options identified to control molybdenum at the mill. The option specifically targets soluble molybdenum associated with oxidized ore by treating the tailings slurry during transport through the tailings delivery line. None of the other sources of molybdenum identified during evaluation of sources (see Section 2) would be addressed by controls implemented by Option 14. Because Option 14 targets soluble molybdenum from oxidized ore and none of the other sources of molybdenum, the option would likely be used in conjunction with another of the options identified to address all sources of molybdenum at Climax prior to discharge of excess water. However, for purposes of this evaluation, Option 14 is considered as a stand-alone control measure.

Under Option 14, chemical reagents would be added to the tailings slurry prior to transfer to the Mayflower TSF. The idea is that the tailings disposal line serves as a chemical reactor to covert dissolved molybdenum, mobilized during the milling process, to a solid phase. When the tailings are deposited in the Mayflower TSF, the solid phase molybdenum would remain with the tailings. Two reagents were evaluated in a series of preliminary laboratory tests, sodium hydrosulfide (NaHS) and ferric oxyhydroxide adsorption.

Samples of whole tailings slurry collected at the mill during the 2017 test were reacted with various doses of the reagents to see how much soluble molybdenum might be precipitated. Results of the sodium hydrosulfide tests indicate that addition of NaHS does not significantly lower the concentration of dissolved molybdenum under these conditions.

In the second set of tests, acidic mine water from 5-Shaft, containing iron, was mixed with higher pH tailings slurry to cause precipitation of ferric oxyhydroxide. A series of samples were prepared with increasing proportions of mine water and the results indicate that when enough water is added to achieve pH 5, concentrations of dissolved Mo around 10,000 µg/L were achieved. The actual extent of molybdenum reduction will depend on the starting concentration of molybdenum in the tailings slurry. Tailings slurry used in the tests was generated from ore with a higher oxidized content than would typically be processed at the mill. Thus, the final potential concentration of molybdenum obtained from addition of 5-Shaft water to the tailings slurry would potentially be lower than 10,000 µg/L.

The results indicate that adding ferric iron (or 5 Shaft water) to the tailings slurry line could limit the concentration of molybdenum in tailings slurry water. As a stand-alone process, the final projected concentration of molybdenum is about 10,000 µg/L when 5 Shaft water is used as the source of iron and acidity, but the result is dependent on the starting concentration of molybdenum in the tailings slurry. Flows in the mine water management system would remain unchanged.

If acidic conditions develop in Mayflower TSF due to the low pH conditions created in the tailings slurry, modification or replacement of the equipment supporting the reclaim pumps and associated pipelines would be necessary. Alternatively, a method to neutralize the pH of the decant pond would be needed to prevent damage to the barge system infrastructure.

Regarding the SBP, Option 14 addresses the following:

- **Influent control measures**: targeting molybdenum suppression in the tailings slurry is a method of influent control by reducing concentrations of molybdenum before the dissolved form enters the broader mine water management system
- **Potential treatment alternatives**: adding chemical reagents to the tailings slurry is an alternative treatment process that might constitute an important step in limiting dissolved molybdenum from oxidized ore
- **Expected effluent quantity**: no changes would be made to the water management system and the effluent flow would peak at 14,000 gpm during snowmelt and average annually about 9,000 gpm
- **Expected effluent quality**: the chemical treatments proposed under Option 14 show the potential to reduce molybdenum concentrations in the tailings slurry water to a range from 5,000 to 10,000 µg/L, subject to the starting concentration of molybdenum in the tailings slurry.

4.0 WATER TREATMENT ALTERNATIVES AND OPTIMIZATION

Stantec conducted a desktop evaluation of available options for treatment of molybdenum at Climax. Six potentially viable treatment processes were included in the evaluation: (1) adsorption of molybdenum with ferric iron precipitate (FeOOH), (2) chemical precipitation of molybdenum with lead (Pb), (3) ion exchange, (4) anaerobic microbial reduction, (5) electrocoagulation, and (6) membrane separation. By application of a set of factors that included cost, nature of process residuals management, process inefficiencies, and ease of implementation; all but the first two options were determined not optional for the Climax facility and were eliminated from further evaluation. A more detailed discussion of the treatment technologies evaluation is included in **Appendix B**.

4.1 ADSORPTION

Adsorption of molybdenum with ferric iron precipitate is considered as the base case technology for Climax since it is already being used to treat molybdenum in mine water (e.g., Brenda Mine [Aube and Stroiazzo, 2000]). Furthermore, the technology has been designed for addition at Climax, and performance of the process is well established. The treatment train for molybdenum adsorption by ferric iron includes the following sequential unit processes:

1. Ferric Iron Coagulation at pH 4.5
2. Alkalization to pH 8
3. Sedimentation
4. Filtration.

This process sequence has potential for incorporation into the existing PDWTP treatment train by utilizing Reactors 1 and 2 for coagulation and alkalization, followed by sedimentation in the Clarifiers and filtration in the Granular Media Filters. If integrating the treatment process into the existing facility is not feasible (this is currently being evaluated), 30% designs have already been designed for a new, separate molybdenum removal plant that would be connected to the PDWTP (Option 1 Section 3.3.1).

Chemical reagents used in the ferric iron adsorption process are ferric sulfate ($Fe_2(SO_4)_3$) and hydrated lime ($Ca(OH)_2$). For removal of manganese (Mn) via chemical oxidation, potassium permanganate ($KMnO_4$) would be added to the process. The main disadvantage of ferric iron adsorption for uptake of soluble molybdenum is the reversibility of the adsorption process, which may result in remobilization and release of soluble molybdenum from the solid precipitate if the solution pH of the treatment residuals storage facility is not maintained within the mildly acidic to circumneutral pH range of 3.0 to 7.5. The sequence of chemical reagent addition is important to prevent the molybdenum desorption before the adsorption solids can be separated from the process stream.

4.3 CHEMICAL PRECIPITATION

Chemical precipitation of hexavalent molybdenum with lead forms the solid $PbMoO_4$. Removal of molybdenum by formation of lead molybdate could be one of the more effective alternative technologies for treatment of molybdenum. The treatment train for this approach includes the following sequential unit processes:

1. Chemical precipitation at pH 10
2. Residual lead scavenging at pH 8
3. Sedimentation
4. Filtration.

This treatment regimen is amenable to implementation in the existing PDWTP infrastructure by utilizing Reactors 1 and 2 for chemical precipitation and residual lead scavenging (e.g., with sulfide such as sodium hydrosulfide [NaSH]), followed by sedimentation in the Clarifiers and filtration in the Granular Media Filters. Chemical reagents used in the $PbMoO_4$ precipitation process are hydrated lime ($Ca(OH)_2$), lead chloride ($PbCl_2$), sulfuric acid (H_2SO_4), and polymer as a flocculant. For removal of residual lead, sodium hydrosulfide (NaHS) is commonly used to scavenge dissolved lead cations from solution; however, there are alternative compounds that eliminate the safety risks associated with handling NaHS. Ferric sulfate ($Fe_2(SO_4)_3$) may also be used as a coagulant for enhanced aggregation and settling of fine particulates, and as a co-precipitant for removal of residual Pb. The primary disadvantage of using lead reagent for treatment of molybdenum is related to lead as a contaminant. Regulatory agencies and primary stakeholders may object to its use for treatment of a source contributing to a drinking water supply.

4.4 OTHER CONSTITUENTS

With regard to other constituents of concern (e.g., cadmium, sulfate) and properties of the effluent that contribute or affect Whole Effluent Toxicity Testing (WET), the treatment technologies assessed herein, and the current water treatment system are variably effective. For example, removal of cadmium is almost quantitative by adsorption to ferric oxyhydroxide at a pH of 7 and higher. Thus, as long as the treatment process has iron either in the influent stream or added as part of the treatment process, cadmium should be removed. If, however, there is insufficient iron in the treatment stream, cadmium removal will likely not be reliable if adsorption to manganese is the primary mechanism.

Treatment processes that rely on lime neutralization, regardless of the target pH of the process, will have limited effect on concentrations of sulfate. The concentration of sulfate in the treatment effluent will reflect an equilibrium concentration with gypsum ($CaSO_4 \cdot 2H_2O$), which for mine waters will be around 1,200 to 2,000 mg/L. Additionally, the ion balance of lime neutralization systems tends toward more hardness (i.e., higher concentrations of calcium and magnesium) due to the addition of calcium associated with lime.

Similarly, potential treatment technologies that could remove soluble molybdenum, need to be implemented in such a manner that conditions for removal of other regulated constituents are not affected. That is, the chemistry of water discharged from Climax is specified in the CDPS permit, and water treatment technologies either already implemented or to be implemented need to consider the full suite of constituents not only a single constituent.

4.5 TREATMENT ALTERNATIVES NOT PURSUED

A brief summary of what evaluations would need to be conducted to fully evaluate those treatment alternatives not pursued is provided in this section.

4.5.1 Ion Exchange

Pilot-scale testing of Mayflower pond water would be required to support a full-scale implementation of the ion exchange process for selective Mo removal. The test protocol would be developed from manufacturer operating recommendation in addition to information that is available from ion exchange extraction work that previously occurred at Climax.

Key objectives of the pilot-scale testing of an ion exchange process would be:

- Determine molybdenum removal efficiency
- Evaluate hydraulic loading
- Analyze column configuration
- Determine exchange resin capacity
- Optimize exchange resin regeneration
- Characterize the regeneration brine waste for disposal

4.5.2 Anaerobic Microbial Reduction of Aqueous Hexavalent Molybdenum

Because of the limitations of this treatment approach, Stantec recommends that any biological treatment testing for molybdenum removal be conducted first at the laboratory scale to determine the broad design criteria for potential implementation. Laboratory testing should provide information on required detention volume (translated to area), low temperature performance, and response to variable influent rate. The preliminary information generated should indicate if application of the technology is feasible within the Climax site-specific constraints. If not, further testing and consideration would not be necessary. If feasible, larger, field-scale testing would be required, potentially implemented in stages to optimize and increase capacity to full-scale requirements.

4.5.3 Electrocoagulation

Pilot-scale testing of Mayflower pond water would be required to prove out the electrocoagulation technology for molybdenum removal at Climax. Testing is needed to determine removal efficiency at various electrical currents, rates of electrode consumption, solids generation rates, and solids separation criteria. A test protocol would need to be developed by Climax with input from equipment suppliers. The test protocol would need to ensure test objectives are clearly stated and that test results provide necessary information for input into required design and engineering, assuming the technology is effective.

4.5.4 Membrane Separation

Other than cost, the key limitation for membrane separation at Climax is the large amount of brine concentrate that is expected to be generated. Based on this limitation, testing of the membrane separation technology should begin at the laboratory scale to determine the actual recovery that can be consistently achieved. Once the recovery is determined, the volume of brine concentrate requiring management could be calculated. Climax would then need to evaluate the possibility of managing the brine on site, that is, disposal options and potential environmental impacts, to determine if the membrane separation technology is feasible within the site constraints. If determined feasible, then pilot-scale testing would be required to fully prove out this technology for possible implementation.

5.0 COST EVALUATION

Stantec will review the existing site infrastructure, including piping, pumping, and treatment systems, to establish where modifications and additions are needed to support the options identified in Section 3.3. These modifications and additions will be documented in an implementation plan for each optimization scenario that will be included in the separate appendix for each option (**Appendices C, D, E, and F**). The implementation plan is necessary since the existing infrastructure cannot incur a prolonged shutdown due to the requirement to maintain water movement through the Climax water management system.

Each implementation plan will include a list of new equipment and equipment modifications (e.g., protective coatings) associated with that option. Where possible, preliminary equipment sizes will be determined to assist with gathering vendor quotes. The implementation plan and vendor quotes will then be evaluated by a Stantec estimator to develop a cost estimate for materials and installation for each optimization option.

Stantec anticipates that the accuracy of the optimization cost estimates will be consistent with an AACE Class 4 level of definition. The corresponding Class 4 accuracy of +50/-30 should allow comparison of alternatives for decision making purposes. In addition, order of magnitude cost estimates for new process chemical reagents will also be developed to understand what changes in operating costs might be incurred. Stantec assumes that labor and power costs will be relatively unchanged unless new equipment (e.g., pump stations), which may have a significantly higher power demand, is introduced to the treatment system(s). Summary costs for the retained options are shown in **Table 9** based on information developed in **Appendices C, D, E, and F**. As described in more detail in this document, all options listed in **Table 9** will require additional testing of the chemical process and engineering design of the infrastructure before a final selection could be made by Climax. The intent of this information included in **Table 9** is to support the WQCC in reducing uncertainty related to the water quality standard for molybdenum to support a water supply use category.

Table 9 Summary of Estimated Costs in 2019 Dollars for Retained Options

Option	Capital Estimate	Annual Operating Estimate	Life Cycle Estimate	Projected Effluent Mo (µg/L)(1)
9 – Buildout Full-Scale Mo Removal Plant(3)	$79,652,000	$2,829,000	$127,100,000	200 to 500
10a – Optimize Existing PDWTP	$26,202,000	$615,325	$35,522,500	200 to 500
10b – Convert Existing PDWTP for $PbMoO_4$ Precipitation	$3,600,000	$1,700,000	$32,638,500	500 to 5,000
13 – Buildout **50%** Capacity Mo Removal Plant	$52,551,000	$1,556,000	$78,137,500	1,000 to 5,000
13 – Buildout **25%** Capacity Mo Removal Plant	$34,671,000	$870,000	$48,977,000	1,000 to 10,000
14 – Reduce Mo in the Tailings Slurry Pipeline	$7,022,000	$6,269,000	$109,988,500	5,000 to 10,000

Notes: (1) projected concentration ranges may change as additional information becomes available, (2) Source of costs for Option 9 are Golder, 2017 escalated to 2019 dollars.

6.0 REFERENCES

Aube, B.C., and J. Stroiazzo. 2000. Molybdenum treatment at Brenda Mines, *in* Proceedings of the 5th International Conference on Acid Rock Drainage. Society for Mining, Metallurgy, and Exploration, Inc. p. 113-1120.

Colorado Water Quality Control Commission. 2013. Policy 13-1: Guidance for Development, Adoption and Review of Discharger Specific Variances. Regulation #31 – Section 31.7(4) (revised 2019).

Golder Associates. 2017. Assessment of Molybdenum Treatment at Climax Mine and Henderson Mill. Report prepared for Climax Molybdenum Company. September 27.

CH2M Hill. 2011. Climax, Property Discharge Water Treatment Plan, Moly-AR Base Case. September 12.

APPENDIX A

Options Matrix and Criteria Evaluation

Climax Mo Removal Options Matrix

Option	Method Summary	Principal SBP Element Addressed	Probable Discharge Concentration (ug/L)	EFFECTIVENESS	TIME TO IMPLEMENT	COST CONSIDERATION	RELIABILITY	OPERABILITY/ PROCESS CONTROL	FLEXIBILITY	WASTE MANAGEMENT	EFFECT ON WATER BALANCE	HYDRAULIC CAPACITY
1	Do not mine oxidized ore	Source control	3,800	Will prevent increase in current Mo concentrations, but does not improve current PDWTP discharge Mo concentrations.	Requires modification of mine plan and wasting of oxide ore. Plan could be implemented within months.	The lost revenue from not mining the oxide ore is greater than the cost for a Mo Removal Plant at the PDWTP location.	Mo concentrations will not improve in the current PDWTP discharge.	Material segregation and handling will be significant.	Management of oxide ore is expected to be extensive.	A new waste stream may develop as a result of stockpiling oxide ore.	The current water balance is not expected to be affected.	A new waste stream may develop as a result of stockpiling oxide ore.
2	Delay mining oxidized ore until Mo removal method is in place	Source control	3,800	Will prevent increase in current Mo concentrations, but does not improve current PDWTP discharge Mo concentrations.	Requires stockpiling of oxide ore. Plan could be implemented within months.	Material stockpiling and handling costs will be significant.	Mo concentrations will not improve in the current PDWTP discharge.	Material segregation and handling will be significant.	Management of oxide ore is expected to be extensive.	A new waste stream may develop as a result of stockpiling oxide ore.	The current water balance is not expected to be affected.	A new waste stream may develop as a result of stockpiling oxide ore.
3	Recover Mo at mill and receive credits; metallurgical process	Water management/blending	3,800	Will prevent increase in current Mo concentrations, but does not improve current PDWTP discharge Mo concentrations.	Requires development of a metallurgical process. Plan could take years.	Metallurgical process could cost more than value of recovered Mo.	Mo concentrations will not improve in the current PDWTP discharge.	Metallurgical extraction process is unknown.	Management and processing of oxide ore is expected to be extensive.	Extraction of Mo from oxide ore will prevent additional waste generation at the PDWTP.	The current water balance is not expected to be affected.	The hydraulic capacity of the water management system is not expected to change.
4	Recover Mo at mill and receive credits utilizing resin	Water management/blending	3,800	Will prevent increase in current Mo concentrations, but does not improve current PDWTP discharge Mo concentrations.	Resin process is understood from previous experience. Plan could be implemented in shorter time period than other metallurgical extraction processes.	Resin process could cost more than value of recovered Mo.	Mo concentrations will not improve in the current PDWTP discharge.	Resin extraction process is known. A process water management plan will need to be developed to determine when water is processed through the resin.	Management and processing of oxide ore Mo is expected to be extensive.	Extraction of Mo from oxide ore will prevent additional waste generation at the PDWTP.	The current water balance is not expected to be affected.	The hydraulic capacity of the water management system is not expected to change.
5	Dry stack or thickened tailings and treat water	Water management/blending	3,800	Will prevent increase in current Mo concentrations, but does not improve current PDWTP discharge Mo concentrations.	A dewatering system and water treatment design and construction could take years to complete.	A combined dewatering system and treatment system could cost more than the Mo Removal Plant at the PDWTP.	Mo concentrations may not improve in the current PDWTP discharge.	Dewatering and treatment processes are known. Dewatering method not identified.	The likely treatment process for Mo removal is capable for variable Mo concentrations.	Removal of Mo from the tailings water at the mill may result in additional waste management.	The current water balance is not expected to be affected.	The hydraulic capacity of the water management system is not expected to change.
6	Install counter current decantation (CCD) system to recirculate high Mo water; Discharge tailing with low molybdenum water	Water management/blending	3,800	Will prevent increase in current Mo concentrations, but does not improve current PDWTP discharge Mo concentrations.	A dewatering system design and construction could take years to complete.	A CCD system could cost as much or more than the Mo Removal Plant at the PDWTP.	Mo concentrations may not improve in the current PDWTP discharge.	CCD process is known.	The CCD process for Mo reduction is capable for variable Mo concentrations.	Discharge of low Mo tailings water should not affect current waste management plans.	The current water balance is not expected to be affected.	The hydraulic capacity of the water management system is not expected to change.
7	Separate high Mo water and use the underground as reactor by combining with 5-Shaft and routing back underground	Water management/blending	3,800	Will prevent some increase in current Mo concentrations, but does not improve current PDWTP discharge Mo concentrations.	A process to separate high Mo water would need to be developed, potentially taking years to implement.	A system to separate high Mo water could cost as much or more than the Mo Removal Plant at the PDWTP.	Mo concentrations may not improve in the current PDWTP discharge. 5 Shaft iron is not in correct form to react with Mo.	The high Mo separation process is controllable. Iron reaction with Mo in the underground workings is not.	Achieving adequate mixing and correct iron form is not possible for variable Mo concentrations.	Removal of Mo in the underground workings should reduce waste generation when compared to high Mo tailings disposal in Mayflower.	The current water balance is not expected to be affected.	The hydraulic capacity of the water management system is not expected to change.
8	Tailings to Tenmile while oxidized ore is mined; Tenmile pool to mill and SDP; SDP re-configured to pH = 4.5, SDP effluent directed to PDWTP	Water treatment; Water management/blending	200 to 3,800	Mo reduction is significant if PDWTP influent is only SDP effluent.	Implementation requires modification of the SDP for acid operation, and installation of a new pipeline to the PDWTP. Could take a year or so to implement.	SDP modification and new pipeline should be less than installation of a full-capacity Mo Removal Plant.	A high level of removal is expected in the SDP. PDWTP discharge Mo reduction will not be as great if water other than SDP effluent is sent to the PDWTP.	The ferric co-precipitation process is straightforward and can be controlled through automation.	The ferric co-precipitation process is adaptable to changing influent Mo concentrations, but has limitations for other metals.	Waste from the SDP will be reduced, but will increase substantially from the PDWTP principally from increased iron and aluminum in the influent	There is a potential that the water balance in the tailings system may not be maintained under certain conditions.	The hydraulic capcity of the existing systems will be sufficient for a portion of the year and insufficient at other times.
9	Buildout PDWTP for Mo removal (per CH2M design)	Water treatment	200 to 500	Mo reduction possibly to range of 200 to 500; all other metals the same	The current status of the Mo Removal WTP design is 30%. It will require several years to complete the design, contract with a construction company, build the new plant, and commission the plant.	This option is the baseline alternative and will be the highest cost of all options carried forward.	The stand alone Mo Removal Plant should provide the highest level of reliability for removal of this constituent.	The ferric co-precipitation process is straightforward and can be controlled through automation.	The ferric co-precipitation process is adaptable to changing influent Mo concentrations, but has limitations for other metals.	The ferric co-precipitation process will increase the total residual solids produced, but not substantially if Mo concentrations in Mayflower do not change.	The Mo Removal Plant will nave no effect on the current water balance/management scheme.	The hydraulic capacity requirements will be met in the basis of design.
10	Modification of 9; all ARD to SDP; modify SDP operations to pH=10 for metals removal; SDP effluent to PDWTP for Mo treatment; adjust WTP flows as necessary to maintain WB	Water treatment optimization	200 to 500	Mo reduction possibly to range of 200 to 500; all other metals removed at SDP	Additional equipment could be implemented in less than one year, possibly in six months.	The cost for new and modified equipment is expected to be substantially less than a new facility.	The modified PDWTP should provide the highest level of reliability for removal of Mo.	The ferric co-precipitation process is straightforward and can be controlled through automation.	The ferric co-precipitation process is adaptable to changing influent Mo concentrations, but has limitations for other metals.	The ferric co-precipitation process will increase the total residual solids produced, but not substantially if Mo concentrations in Mayflower do not change.	The Mo Removal Plant will nave no affect on the current water balance/management scheme.	The hydraulic capacity requirements will be met in the basis of design.
11	Reconfigure flows to route lowest Mo concentrations to PDWTP; Modify SDP to pH = 4.5, SDP effluent flows to PDWTP via Tenmile; Flows with highest Mo go through Mayflower and Mill and become the influent to the SDP.	Water treatment; Water management/blending	500 to 1,000	Mo reduction to range from 500 to 1,000; all other metals removed at PDWTP	SDP modifications include making tank and piping internals compatible with pH 4.5 solution, requiring temporary plant shutdown. A pipeline from the SDP to the PDWTP will also need to be constructed It is expected that the necessary modifications could occur within one year after a plan is developed.	The cost for necessary modifications is expected to be less than $20 million, substantially less than a new facility.	The modified SDP process for Mo removal will reliably remove this consituent as long as adequate ferric iron is present. However, Mo inputs to Tenmile will not be fully addressed.	The SDP operation will be highly controllable by automation. The limited control of Tenmile Mo concentrations could be an issue.	The ferric co-precipitation process is adaptable to changing influent Mo concentrations to the SDP, but there will be limitations associated with Tenmile.	The ferric co-precipitation process will increase the total residual solids produced, but not substantially if Mo concentrations in the system do not change.	The Mo Removal process is expected to have minimal effect on the current water balance/management scheme. Water availability from Tenmile needs to be validated in WB model.	Since no new plants are to be constructed, it is assumed that existing plant capacities will be sufficient. A potential derating of the maximum PDWTP capacity may be needed.
12	ARD and Tenmile to SDP; Modify SDP operations to pH = 10 for Mn; SDP effluent directly to modified PDWTP for Mo treatment at pH 4.5; Supplemental flow from Mayflower to PDWTP to maintain WB; Mill to Mayflower and back.	Water treatment optimization	200 to 500	Mo reduction possibly to range of 200 to 500; all other metals removed at SDP	PDWTP modifications include making tank and piping internals compatible with pH 4.5 solution, requiring temporary plant shutdown. A pipeline from the SDP to the PDWTP will also need to be constructed. It is expected that the necessary modifications could occur within one year after a plan is developed.	The cost for necessary modifications is expected to be substantially less than a new facility.	The modified PDWTP should provide the highest level of reliability for removal of this constituent.	The ferric co-precipitation and chemical oxidation processes are straightforward and can be easily controlled through automation.	The ferric co-precipitation and chemical oxidation processes are adaptable to changing influent Mo and Mn concentrations, but have limitations for other metals.	The ferric co-precipitation process will add to the total residual solids produced, but may be offset if Mayflower Mn does not have to be removed by PDWTP.	The modified PDWTP approach is expected to have minimal effect on the current water balance/management scheme. Water availability from Mayflower needs to be validated in WB model.	Since no new plants are to be constructed, it is assumed that existing plant capacities will be sufficient. A potential derating of the maximum PDWTP capacity may be needed.
13	Buildout PDWTP Mo water treatment plant at reduced capacity to run in conjunction with metals removal system at the PDWTP; influent flow to Mo plant varies seasonally in a slip-stream mode and will produce intermediate Mo concentrations during high-flow periods.	Water treatment optimization	1,000 to 5,000	Mo removal will be substantial if all flow is routed to the reduced capacity Mo Removal Plant. Overall Mo removal decreases substantially if the split stream flow is significant.	The current status of the Mo Removal WTP design is 30%. It will require several years to complete the design, contract with a construction company, build the new plant, and commission the plant.	This option may result in savings up to 50% when compared to the full capacity build out option, depending on the ultimate capacity.	The reduced capacity Mo Removal Plant should provide the highest level of reliability for removal of Mo when all flow is routed through the plant.	The ferric co-precipitation process is straightforward and can be controlled through automation.	The ferric co-precipitation process is adaptable to changing influent Mo concentrations, but has limitations for other metals.	The ferric co-precipitation process will increase the total residual solids produced, but not substantially if Mo concentrations in Mayflower do not change.	The Mo Removal Plant will have no effect on the current water balance/management scheme.	By definition, the split-stream approach does not meet hydraulic capacity requirements.
14	Use Mayflower TSF as reactor, add chemicals to #1 Drop Box, use tailing line as a reactor to remove soluble Mo and deposit Mo in Mayflower TSF	Treatment alternatives	5,000 to 10,000	Mo reduction to range of 5,000 to 10,000; all other metals removed at SDP & PDWTP	Additional equipment could be implemented in less than one year, possibly in six months.	The cost for new equipment is expected to be substantially less than a new facility.	The lack of process control in the pipeline and likely volatility of Mo concentration reduce reliability.	Control of aqueous chemistry is unknown in the presence of high tailing solids concentrations.	Chemical additions can be varied, but lack of control of tailing flow and composition is a limitation.	Additional solids to be generated will be directly deposisted in Mayflower with no further handling required.	Treatment in the Tailings Line should have no effect on the current water balance/management scheme.	This option should not have any hydraulic limitations.
15	All ARD to SDP; modify SDP operations to pH = 10 to remove Mn; SDP to Tenmile; Tenmile to Mill; Mill to Mayflower and back; Mayflower to modified PDWTP which is upgraded for Mo removal (pH = 4.5).	Water treatment optimization	200 to 500	Mo reduction possibly to 200; all other metals removed at SDP	PDWTP modifications include making tank and piping internals compatible with pH 4.5 solution, requiring temporary plant shutdown. It is expected that the necessary modifications could occur within one year after a plan is developed.	The cost for necessary modifications is expected to be substantially less than a new facility.	The modified PDWTP should provide the highest level of reliability for removal of this constituent. Modified SDP operation is not expected to involve any equipment changes or upgrades.	The ferric co-precipitation, chemical oxidation, and pH adjustment processes are straightforward and can be controlled through instrumentation and automation.	The ferric co-precipitation and chemical oxidation processes are adaptable to changing influent Mo and Mn concentrations, but have limitations for other metals.	The ferric co-precipitation process will add to the total residual solids produced at the PDWTP.	The impending closure of Tenmile TSF eliminates this location for receiving SDP effluent, resulting in the need for an alternate location to receive SDP effluent. The effect on site-wide water balance is uncertain.	Since no new plants are to be constructed, it is assumed that existing plant capacities will be sufficient. A potential derating of the maximum PDWTP capacity may be needed.
16	All ARD to SDP; modify SDP operations to pH = 10 to remove Mn; SDP to Tenmile; Tenmile is only source to Mill; Mill to Mayflower; Mayflower to modified PDWTP which is upgraded for Mo removal (pH = 4.5).	Water treatment optimization	200 to 500	Mo reduction possibly to range of 200 tp 500; all other metals removed at SDP	PDWTP modifications include making tank and piping internals compatible with pH 4.5 solution, requiring temporary plant shutdown. It is expected that the necessary modifications could occur within one year after a plan is developed.	The cost for necessary modifications is expected to be substantially less than a new facility.	The modified PDWTP should provide the highest level of reliability for removal of this constituent. Modified SDP operation is not expected to involve any equipment changes or upgrades.	The ferric co-precipitation, chemical oxidation, and pH adjustment processes are straightforward and can be controlled through instrumentation and automation.	The ferric co-precipitation and chemical oxidation processes are adaptable to changing influent Mo and Mn concentrations, but have limitations for other metals.	The ferric co-precipitation process will add to the total residual solids produced at the PDWTP.	The impending closure of Tenmile TSF eliminates this location for receiving SDP effluent, resulting in the need for an alternate location to receive SDP effluent. The effect on site-wide water balance is uncertain.	Since no new plants are to be constructed, it is assumed that existing plant capacities will be sufficient. A potential derating of the maximum PDWTP capacity may be needed.
17	Alternative 1 - WQCC Policy 13-1: Consider an alternative location for the discharge water, including a body of water with more assimilative capacity	Water management	Varies depending on available assimilative capacity	Potential, practical alternative discharge locations are the Eagle and Arkansas River basins. It is not expected that these basins will provide more assimilative capacity than Tenmile Creek. A third potential water body is Dillon Reservoir which currently receives flow from Tenmile Creek. A direct discharge to Dillon Reservoir would improve conditions in Tenmile Creek, but not Dillon Reservoir. However, the assimilative capacity of Dillon Reservoir is expected to be greater than Tenmile Creek.	Discharge to Dillon Reservoir would require an approximate 12 mile long pipeline that is expected to take years to plan, align, permit, design, and construct.	The cost for a pipeline to Dillon Reservoir is expected to be comparable or greater than implementation of a new treatment plant.	Since the PDWTP is the principal contributor of Mo to the Tenmile Creek, piping the effluent to Dillon Reservoir is considered highly reliable for decreasing Mo to Tenmile.	Assuming that flow in the pipeline is by gravity, the operational aspects are straightforward. However, Denver Water uses Dillon Reservoir as a water supply, so there are other considerations (including water rights concerns) that would need to be evaluated.	The pipeline would be sized for the highest effluent flow rate from the PDWTP and is thus flexible for all flow rates.	No waste will result from operating the pipeline discharge to Dillon Reservoir.	No effect on the water balance is expected.	The hydraulic capacity of the water management system is not expected to change.
18	Alternative 2 - WQCC Policy 13-1: Consolidate discharge with another WWTP	Water management/water treatment alternatives	No improvement	The Blue River Wastewater Treatment Plant is the largest capacity plant near the PDWTP with a capacity of 4 million gallons per day (MGD). The hydraulic design of the PDWTP is 21 MGD, 500 percent greater than the Blue River WWTP. This disparity in plant capacities rules this option out from further consideration. Further, even if the Blue River WWTP had capacity to receive effluent from Climax, it is unlikely there would be any improvement in water quality, as the WWTP is designed to treat municipal waste water not mine waste water. Thus, the WWTP does not specifically treat for molybdenum. Additionally, the Blue River WWTP could not be forced to take the effluent even if capacity existed.								

Climax Mo Removal Options Matrix

Option	Method Summary	Principal SBP Element Addressed	Probable Discharge Concentration (ug/L)	EFFECTIVENESS	TIME TO IMPLEMENT	COST CONSIDERATION	RELIABILITY	OPERABILITY/ PROCESS CONTROL	FLEXIBILITY	WASTE MANAGEMENT	EFFECT ON WATER BALANCE	HYDRAULIC CAPACITY
19	Alternative 3 - WQCC Policy 13-1: Reduce the amount of water discharged	Water management	Likely higher than current conditions	The most effective method to reduce the amount of water discharged is to decrease the collection area of the tailings storage facilities. Closing and covering a tailings facility would allow clean precipitation to be shed from the system. The current mine reclamation plan includes closure of the Tenmile TSF in the near future, a measure that is expected to reduce the volume of water requiring management and treatment in the system. However, the current mine plan keep the overall facility open and in operation , meaning there will remain excess water that must be discharged from the Climax system.	Planning, design, and construction related to closure of the Tenmile TSF will take years.	Closure of the Tenmile TSF is expected to be required at some time in the mine life and is thus not considered an optional cost expenditure.	Reducing the volume of water discharge via closure of the Tenmile Tailings Storage facility will reduce the annual mass of molybdenum discharged, but would have no effect on the discharge concentration.	Reducing the volume of water requiring management improves the overall site operability in terms of moving water, in addition to decreasing the throughput requirements at the PDWTP.	A reduced amount of water to discharge creates additional flexibility in water throughput requirements at the PDWTP.	Waste management is expected to decrease from the reduction of water discharge.	The water balance is not expected to be significantly changed, except that pond water associated with the Tenmile TSF will no longer be a component of the water management system.	The hydraulic capacity of existing infrastucture should not be affected by reducing the amount of water discharged.
20	Alternative 4 - WQCC Policy 13-1: Consider water recycling measures	Water management	Minor reduction compared to current conditions if any	Water recycling typically offsets water import requirements for a mining operation. Climax has been decreasing the amount of water it imports into their system (for use during the dry season and when water rights and storage obligations cannot be met) in recent years, averaging 13% of the annual amount discharged from the PDWTP from 2015 to 2017. Further decreasing the amount of water import to the site presents a risk to the Climax milling operation in that a lack of water availability could shut down the mining operation. Given this risk, and that the amount of potential reduction in discharge is considered minor, this alternative is not viable, particularly since other options are available that do not present this risk.								
21	Alternative 5 - WQCC Policy 13-1: Consider reclaiming water for reuse	Water management	No change	Process water input to the milling operation is supplied by the reclaim system of pumps and decants on the Tenmile and Mayflower Tailings Ponds. Thus, further evaluation reclaiming water for reuse is not further evaluated as water reclaim is already occurring to the maximum extent.								
22	Alternative 6 - WQCC Policy 13-1: Process change, raw material substitution, or alternatively technology to minimize the source of the pollutant	Source control	Varies (see previous options)	The primary source of soluble molybdenum in the water management system is tailings material. Various alternatives for reducing molybdenum from the mining process are presented in Options 1 through 6. An additional measure for source control is closure and covering the tailings storage facilities, as presented in Option 19 as part of the Tenmile TSF closure. Since this option is evaluated in several other options presented in this matrix, no further evaluation is considered.								
23	Alternative 7 - WQCC Policy 13-1: Standard treatment methods	Water treatment alternatives or optimizations	Varies potentially 200 - 500 (see previous options)	The build out of the Mo Removal Plant at the PDWTP is the standard treatment method for molybdenum removal. This option is a duplicate of Option 9. Refer to Option 9 for the evaluation of standard treatment method.								
24	Alternative 8 - WQCC Policy 13-1: Innovative or alternative methods of treatment and advanced treatment, including new designs, stages, components, capacity for treatment plant replacement or upgrade of current plant	Water treatment alternatives or optimizations	Varies potentially 200 - 500 (see previous options)	Other treatment methods, including RO, IX, and EC, are evaluated in Sectio 4 (Water Treatment Alternatives Optimzation) of the SBP report. Optimizations of the existing facilities for improved molybdenum removal are presented in Options 10 through 16. Thus, no further evaluation of other treatment methods and upgrades to existing facilities is considered.								
25	Alternative 9 - WQCC Policy 13-1: Improved operation and maintenance of existing facilities in order to maximize treatment of removal of the pollutant	Water treatment alternatives or optimizations	Varies potentially 200 - 500 (see previous options)	Optimizations of the existing facilities for improved molybdenum removal are presented in Options 10 through 16. Thus, no further evaluation of other treatment methods and upgrades to existing facilities is considered.								
26	Alternative 10 - WQCC Policy 13-1: Seasonal or controlled discharge options to minimize discharging during critical water quality periods	Water management	No change likely	The PDWTP treatment and discharge operation supports water management objectives at Climax by maintaining tailings pond elevations (Mayflower, in particular) through variable seasonal throughput. The range of flows through the PDWTP is from 14,500 gpm during spring snowmelt down to approximately 25% of that capacity in drier periods of the year. The actual water treatment rate is based on water rights and storage obligations, and is already optimized. Thus, variable seasonal discharge rates will not be further evaluated.								
27	Alternative 11 - WQCC Policy 13-1: Watershed trading	Water management	No change likely	The basis for reducing molybdenum loading to Tenmile Creek is meeting the water supply use category for protection of human health. Watershed trading, while applicable in many situations, is not expected to address questions involving protection of human health. Thus, this option will not be further evaluated.								
28	Alternative 12 - WQCC Policy 13-1: Land application of wastewater	Water treatment alternatives or optimizations	Not feasible	Land application of wastewater requires flat areas to promote infiltration and eliminate overland flow. Climax has no suitable flat areas with thick extensive soils available for land application particularly for the large flows that occur during spring melt. Additionally, land application is not suitable during the winter months when multiple feet of snow accumulates at Climax. Thus, land application of wastewater is not further evaluated.								
29	Alternative 13 - WQCC Policy 13-1: Total containment of wastewater	Water management	Not feasible	Presently, all mine process water is segregated from clean water and contained with the various mine facilities. Water rights and storage obligations, including tailings dam operational criteria, require discharge of mine process water from the water management system. The PDWTP supports water discharge from the water management system since the only available water that can be discharged to Tenmile Creek contains constituents of concern. Thus, indefinite containment of all mine process water is not further evaluated.								
30	Alternative 14 - WQCC Policy 13-1: Other alternatives to minimize the effects of the proposed discharge activity	Water management, treatment alternatives or optimizations	Varies (see previous options)	Options 1 through 16 are a comprehensive list of alternatives that have been developed to reduce molybdenum concentrations in the water management system and PDWTP discharge to Tenmile Creek. One additional alternative to minimize the effects of the proposed discharge activity would be to cease mining. This is not a feasible alternative, as it would have economic ramifications in Summit County, statewide, nationwide, and worldwide. Additionally, molybdenum concentrations are expected to continue even after the life of the mine.								
31	Alternative 15 - WQCC Policy 13-1: No action	Not applicable	No improvement	A No Action option would result in increased molybdenum concentrations in the Climax water management system and PDWTP effluent due to the mining of oxidized ore. Current conditions and potentially higher molybdenum concentrations would prevail.								

NOTES

COST CONSIDERATION - Estimated relative cost to implement option.
RELIABILITY - Ability to consistently produce desired results.
FLEXIBILITY - Ability to adapt to changing conditions.
OPERABILITY/PROCESS CONTROL - Is the option optimized to achieve desired results?
EFFECTIVENESS - Expected Mo concentrations in effluent; affect on other constituents.
AFFECT ON WATER BALANCE - Will the site wide water management strategy continue to apply?
WASTE MANAGEMENT - Type and amount of waste generated.
HYDRAULIC CAPACITY - How the option works within the current system hydraulic constraints.
Probable Discahrge Concentration for Options 1-7 is based on the current maximum concentration recorded in effluent from the PDWTP

APPENDIX B

Water Treatment Technologies Assessment

Stantec

Technical Memorandum

To:	Ray Lazuk	From:	Phil Johnson, Dan Dupon and Jim Finley
	Climax Molybdenum Company		Stantec
File:	233001306	Date:	December 5, 2018 revised March 7, 2019

Reference: Evaluation of Molybdenum Water Treatment Alternatives for Climax

INTRODUCTION

This technical memorandum provides an analysis and summary of available molybdenum treatment technologies for consideration at the Climax Mine (Climax). Climax is conducting test work on the effectiveness of sodium hydrosulfide (NaHS) to suppress soluble Mo in the oxide tailing. In this technical memorandum, the available treatment processes are discussed in terms of ease of implementation, effectiveness, and compatibility with the Sludge Densification Plant (SDP) and Property Discharge Water Treatment Plant (PDWTP) at Climax.

AQUEOUS CHEMISTRY OF MOLYBDENUM

GEOCHEMICAL PROPERTIES OF MOLYBDENUM

Molybdenum (Mo) is a reactive metallic element that can exist in a variety of chemical oxidation states ranging from -2 to +6 [Mitchell, 1973]. Mo coordinates with 4 to 8 neighboring atoms, and readily reacts with most inorganic and organic ligands to form a broad spectrum of monomeric and polymeric compounds. In the near-surface geologic environment, the predominant electronic valences for Mo-bearing minerals are the hexavalent (+6) and quadrivalent (+4) oxidation states. Naturally occurring minerals having quadrivalent Mo correspond to reducing geochemical conditions, whereas Mo in its hexavalent state is associated with Mo-bearing minerals exposed to oxidizing conditions.

Molybdenum has been identified as a chief elemental component in more than a dozen different minerals, among which quadrivalent molybdenite (MoS_2) is by far the most abundant Mo-bearing ore mineral [Killeffer and Linz, 1952]. Molybdenite is typically found in endogenic ore deposits along with pyrite and associated sulfidic ore minerals [Turekian and Wedepol, 1961]. Some other naturally occurring molybdenum minerals that contain hexavalent Mo are wulfenite ($PbMoO_4$), powellite ($CaMoO_4$), ferrimolybdite ($Fe_2(MoO_4)_3{\cdot}7H_2O$), molybdite ($MoO_3$), ilsemannite ($Mo_3O_8{\cdot}nH_2O$), and sidwillite ($MoO_3{\cdot}2H_2O$). Hexavalent Mo minerals appear in localized oxidation zones of molybdenite-bearing ore bodies and therefore, are generally of minor significance in terms of natural abundance.

Endogenic porphyry ore deposits containing molybdenite are the primary source of Mo. This type of mineralization typically occurs in stockworks, veinlets, and disseminations contained in igneous intrusive rocks. At Climax, the molybdenite is found within a stockwork of silica-rich veinlets disseminated in an altered matrix of alkaline rhyolites and granites [White et al., 1981]. Like most metal sulfide ore minerals, molybdenite is totally insoluble in water.

Localized zones of oxidization containing hexavalent Mo minerals are interspersed within the Climax ore body. As is the case with most oxide ore minerals, hexavalent Mo minerals have low solubility in circumneutral-pH water, but undergo enhanced solubility under acidic conditions due to protonation and hydrolysis reactions [Staples, 1951]. Because of this property of oxide ore minerals, Mo in the hexavalent state is also referred to as ***acid soluble molybdenum***.

When Mo-bearing oxide ore minerals dissolve in water, the Mo atom coordinates with four oxygen atoms to form the molybdate oxyanion (MoO_4^{2-}). Molybdate is the most soluble oxidation state for Mo and is the predominant form of dissolved Mo contained in water impacted by mine operations at Climax.

ACID/BASE PROPERTIES OF AQUEOUS HEXAVALENT MOLYBDENUM

Under mildly acidic conditions, the molybdate oxyanion hydrolyzes in water to form a soluble diprotic acid known as molybdic acid (H_2MoO_4). The acid/base properties of hexavalent Mo exert a considerable influence on dictating the treatment regimen for Mo, since variations in acidity of a few pH units can result in significant changes in distribution among the three forms of hexavalent Mo: H_2MoO_4, $HMoO_4^-$, and MoO_4^{2-}.

Figure 1 shows the speciation diagram for hexavalent Mo in aqueous solution as a function of pH. The dominant type of hexavalent Mo above pH 5 is the molybdate anion. At pH 4, there is an equal distribution between the three species of hexavalent Mo. Below pH 3, molybdic acid is the dominant species. The relative distribution of hexavalent Mo species is known to exert a significant impact on treatment effectiveness because of differences in the physical and chemical properties among the various species. Effective control of solution pH is therefore key to the success of any Mo removal process.

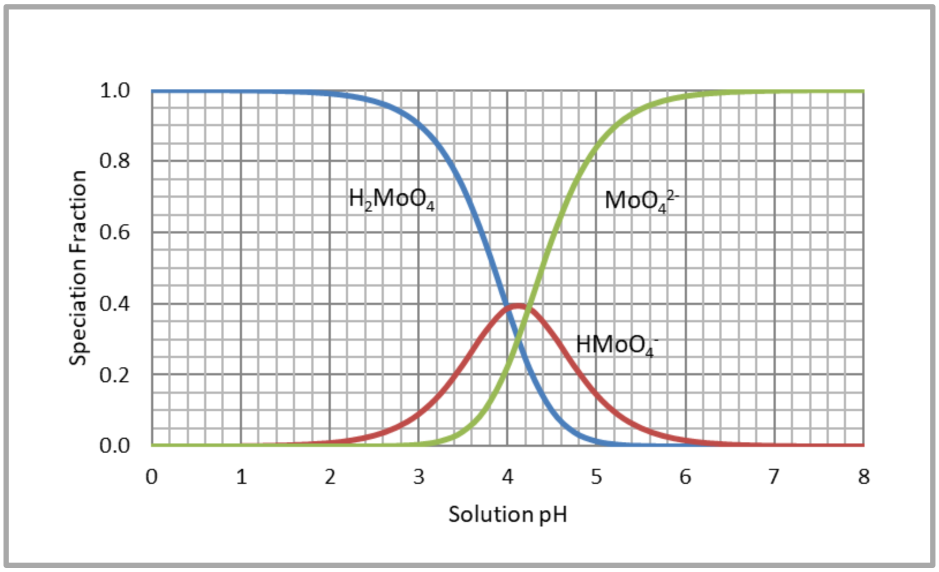

Figure 1: Speciation Diagram for Aqueous Hexavalent Mo

SURVEY OF MOLYBDENUM TREATMENT ALTERNATIVES

This survey of available Mo treatment technologies for Climax considered the following processes:

- Ferric Iron Sequestration
- Chemical Precipitation
- Ion Exchange
- Anaerobic Microbial Reduction
- Electrocoagulation
- Membrane Separation.

SEQUESTRATION OF HEXAVALENT MO WITH FERRIC IRON

Ferric iron sequestration is a hybrid physicochemical treatment process that includes the uptake of dissolved metal cations and metalloid oxyanions by ferric hydroxide particulates. Ferric hydroxide, or ***ferrihydrite*** ($Fe(OH)_3$) is a microcrystalline form of ferric iron (Fe^{3+}) that hydrolyzes in water to form an insoluble solid precipitate [Cornell and Schwertmann, 2003]. Deposition mechanisms for metal cations and metalloid oxyanions with ferrihydrite solids include chemical co-precipitation and electrostatic adsorption. Co-precipitation is a chemical process that involves the formation of strong ionic bonds between oppositely charged ions in solution to generate chemically stable, insoluble ionic solids. Adsorption is a physical process that involves weak, reversible electrostatic attractive forces between charged ions in solution and oppositely charged functional groups on mineral surfaces.

When ferric iron is added to water to form ferrihydrite precipitate, concurrent reactions involving chemical precipitation (i.e. co-precipitation) and electrostatic adsorption of specific types of metal cations and/or metalloid oxyanions onto ferrihydrite particulates will take place if the solution chemistry is suitable.

Dissolved ionic constituents that are amenable to removal using ferrihydrite include the following categories:

- Divalent heavy metal cations such as nickel (Ni^{2+}), copper (Cu^{2+}), cadmium (Cd^{2+}), zinc (Zn^{2+}), and lead (Pb^{2+}), and;
- Acidic metalloid oxyanions such as arsenate (AsO_4^{3-}), selenite (SeO_3^{2-}), chromate (CrO_4^{2-}), and molybdate (MoO_4^{2-}).

The dominant removal mechanism for heavy metal cations is chemical co-precipitation; whereas, electrostatic adsorption is the principal mechanism for uptake of metalloid oxyanions by ferrihydrite.

Published results of laboratory treatability studies indicate that ferric iron adsorption is an effective treatment for hexavalent Mo under mildly acidic conditions [Aube and Stroiazzo, 2000]. The optimum pH range for adsorption of hexavalent Mo with ferrihydrite is 4.0 to 5.0, with an optimum ferric iron dose corresponding to an Fe:Mo mass ratio of 4 to 8 parts of iron to 1 part of molybdenum. Under these test conditions, the ferrihydrite adsorption process reduced the dissolved concentration of hexavalent Mo from an initial value of 2.7 mg/L to a final value of 0.15 mg/L.

Unpublished laboratory benchtop experiments recently conducted by Stantec indicate that excursions in solution pH outside the range of 3.0 to 7.5 will cause previously adsorbed molybdate to detach (desorb) from the ferrihydrite precipitate and re-dissolve in the water column. The remobilization of hexavalent Mo can be attributed to the following electrostatic desorption mechanisms:

1. Conversion of adsorbed molybdate (MoO_4^{2-}) and bimolybdate ($HMoO_4^{-}$) anions to uncharged molybdic acid (H_2MoO_4) below pH 3.0. Desorption is driven by the loss of electrostatic attraction between the positively charged surface functional groups on ferrihydrite particulates and the negatively charged molybdate and bimolybdate ions.
2. Charge reversal of ferrihydrite surface functional groups above pH 7.5. When solution pH is increased above 7.5, the charged functional groups exposed on the surface of ferrihydrite particles undergo deprotonation reactions, resulting in reversal of charge from positive to negative. This charge reversal induces desorption of Mo due to electrostatic repulsion between negatively charged surface functional groups and negatively charged molybdate anions.

Treatment by adsorption to the surface of precipitated ferric hydroxide has been substantiated under laboratory test conditions to produce an effluent Mo concentration below 500 µg/L. Because of the effectiveness of the ferrihydrite adsorption reaction and the fact that the current serendipitous treatment of Mo at Climax is based on the same process, ferric iron adsorption is recommended for further evaluation as a potentially viable treatment option for soluble Mo at Climax.

The primary advantages of ferrihydrite adsorption for treatment of Mo at Climax are:

- The ferrihydrite adsorption process can be incorporated into the existing two-stage (SDP and PDWTP) treatment systems.
- The chemical reagents required for ferric iron adsorption are standard chemicals that are widely used in the mining industry. Sulfuric acid (H_2SO_4) would be used for pH adjustment, and ferric sulfate ($Fe_2(SO_4)_3$) would be used for generation of ferrihydrite precipitate (assuming that raw water iron concentrations are insufficient to meet the Fe dosage requirement).
- Ferrihydrite adsorption is recognized as a “best available technology” for treatment of soluble Mo.
- Mo concentrations that are less than the current value discussed by the Colorado Department of Public Health and Environment (CDPHE) of 0.21 mg/L are theoretically achievable using ferrihydrite.

Some notable disadvantages of ferric iron adsorption for treatment of dissolved hexavalent Mo are:

- The reversibility of the electrostatic adsorption process may result in remobilization and release of soluble Mo from the solid precipitate if solution pH is not maintained within the mildly acidic to circumneutral range of 3.0 to 7.5.

- The optimum effectiveness of ferrihydrite adsorption for uptake of soluble Mo is restricted to the narrow pH band of 4.0 to 5.0.

Treatment Train for Ferric Iron Adsorption. The sequential unit processes required for adsorption of hexavalent Mo with ferrihydrite are: Chemical Addition → Coprecipitation/Adsorption → Sedimentation → Filtration. Chemical reagents used in the ferric iron adsorption process include ferric sulfate and sulfuric acid. Treated effluent is slightly acidic and will require pH adjustment with lime or caustic soda prior to discharge. Process residuals consisting of ferrihydrite sludge will require dewatering prior to disposal. This treatment regimen is compatible with the existing treatment process used at the Climax PDWTP, which consists of an alkalization tank, two reactors-in-series, solids clarifier, and granular media filters. Therefore, the ferric iron adsorption treatment process could be incorporated into the existing treatment regimen by adding components to the system but without the need for additional major unit processes.

Ferric Iron Adsorption Residuals Management. The potential for remobilization of Mo has implications for long-term storage of residual solids at Climax, wherein pore water can undergo significant changes in pH as meteoric water causes chemical oxidation reactions with sulfide minerals that generate acidic conditions. In order to minimize the likelihood of Mo remobilization, dewatered solids containing Mo-laden ferrihydrite may require a dedicated solids storage cell where the contents are fully contained and isolated from run-on and run-off water.

CHEMICAL PRECIPITATION OF AQUEOUS HEXAVALENT MO WITH METAL CATIONS

Selective removal of dissolved hexavalent Mo can be achieved by chemical precipitation of ionic solids composed of molybdate anions and metal cations. Solubility and precipitation of ionic solids in water is characterized and quantified by a chemical parameter known as the ***solubility product***. Published values of the solubility product for metal cation/molybdate compounds and associated ionic solids of competing anions provide the discriminatory metric for evaluating and identifying the appropriate metal cations for selective precipitation of soluble Mo. At Climax, the principal anions competing with molybdate for metal cations are sulfate (2,100 mg/L), carbonate, and hydroxide (with the latter two anions having greater relevance under alkaline conditions).

Table 1 contains a comprehensive list of published values of metal cation solubility products that form insoluble ionic compounds with molybdate (MoO_4^{2-}), sulfate (SO_4^{2-}), carbonate (CO_3^{2-}), and hydroxide (OH^-) anions.

Table 1: Solubility Products for Ionic Solids of Molybdate, Sulfate, Carbonate, and Hydroxide

Metal Cation (Me^{2+})	$MeMoO_4(s)$	$MeSO_4(s)$	$MeCO_3(s)$	$Me(OH)_2(s)$
Calcium (Ca^{2+})	1.45×10^{-8}	3.16×10^{-5}	3.36×10^{-9}	5.50×10^{-6}
Strontium (Sr^{2+})	2.00×10^{-7}	3.47×10^{-7}	5.60×10^{-10}	1.70×10^{-4}
Barium (Ba^{2+})	3.55×10^{-8}	1.07×10^{-10}	2.58×10^{-9}	2.57×10^{-4}
Zinc (Zn^{2+})	6.31×10^{-5}	7.26×10^{-1}	1.46×10^{-10}	3.16×10^{-16}
Lead (Pb^{2+})	1.20×10^{-13}	2.51×10^{-8}	7.40×10^{-14}	1.45×10^{-15}

Table 1 Notes:

1. Published value for $PbMoO_4$ was obtained from Chao and Chen (1977). Published values for remaining $MeMoO_4$ ionic solids were obtained from Wagman et al. (1982) and Lange (1969).
2. Published values for $MeSO_4$, $MeCO_3$ and $Me(OH)_2$ were obtained from Wagman et al. (1982) and Lange (1969).

The key discriminants used for ranking the metal cations in terms of effectiveness for selective precipitation of hexavalent Mo are:

1) Metal cation/molybdate compounds having the lowest solubility product values, and;

2) Solubility product values for metal cation/sulfate compounds that are significantly larger than the corresponding value for the metal cation/molybdate compound.

A comparison of the solubility products shown on **Table 1** suggests that *calcium* and *lead* are the best candidates for selective precipitation of hexavalent Mo. These two metal cations were chosen for additional evaluation to determine their relative effectiveness for treatment of Mo at Climax.

Figures 2 and 3 illustrate the conditional solubility for hexavalent Mo versus solution pH for the ionic solids calcium molybdate ($CaMoO_4$(s)) and lead molybdate ($PbMoO_4$(s)).

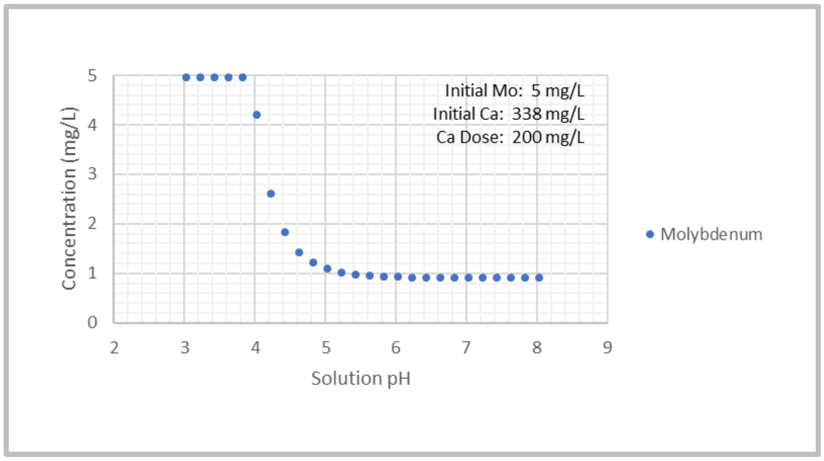

Figure 2: Mo Concentrations in Equilibrium with Calcium Molybdate Solids

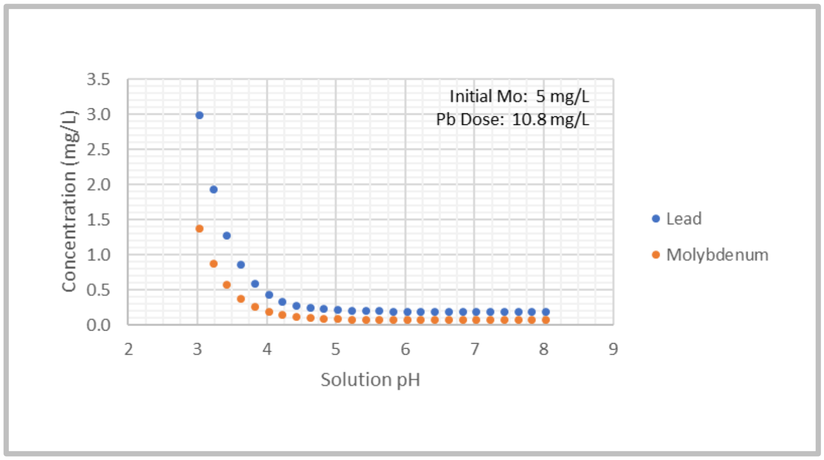

Figure 3: Mo and Pb Concentrations in Equilibrium with Lead Molybdate Solids

In the comparative analysis, reported dissolved ion concentrations in effluent from the Climax SDP were used:

- Total dissolved solids: 3,500 mg/L
- Calcium: 338 mg/L
- Sulfate: 2,100 mg/L
- Molybdenum: 5 mg/L

For precipitation of calcium molybdate, the calcium (Ca) dose is limited by precipitation of gypsum ($CaSO_4 \cdot 2H_2O$). The maximum Ca dose that can be added to the SDP process before gypsum begins to precipitate is 200 mg/L. Under these conditions, the minimum Mo concentration that can be theoretically achieved is 1 mg/L for solution pH greater than 5.0. Because the predicted minimum concentration of Mo by Ca addition remains at or above 1,000 µg/L, the method has not been included for further evaluation as a treatment option for soluble Mo.

For precipitation of lead molybdate, a lead (Pb) dose of 10.8 mg/L was used to calculate the conditional solubility of Mo. This value for Pb corresponds to the equivalent molar concentration of 5 mg/L Mo, which is 5.2×10^{-5} moles/L. The theoretical analysis shows that a Mo concentration of 0.1 mg/L can be achieved for solution pH values greater than 5.0. The residual Pb concentration under this treatment scenario is 0.22 mg/L and may be lower if adsorption to ferric iron solids is considered. Because the predicted minimum concentration of Mo by Pb addition is less than 1.000 µg/L, the method has been included for further evaluation as a potential treatment option for soluble Mo.

Chemical Precipitation Treatability Tests

Stantec staff recently conducted a series of laboratory-scale treatability tests involving chemical precipitation of hexavalent Mo with Pb. In the laboratory benchtop procedure, lead chloride ($PbCl_2$) salt was used as the reagent for soluble Pb, and sodium molybdate (Na_2MoO_4) salt was the source for soluble Mo. A background electrolyte matrix containing 2,100 mg/L sulfate was used in the experiments to simulate the solution chemistry of the SDP treatment process at Climax.

The test procedure involved titrimetric addition of Pb reagent to the electrolyte matrix containing 10 mg/L Mo. The Pb reagent solution used as the titrant contained 0.54 mg Pb/mL. Titrations consisted of stepwise sequential addition of Pb reagent and measurement of pH, electrical conductivity, oxidation/reduction potential, and turbidity. Separate titrations were performed at matrix pH values of 4, 7, and 10 using 500 mL of solution for each test. The initial matrix pH for each titration was achieved by addition of sulfuric acid (H_2SO_4) and sodium hydroxide (NaOH). The test results for turbidity are shown on **Figure 4**.

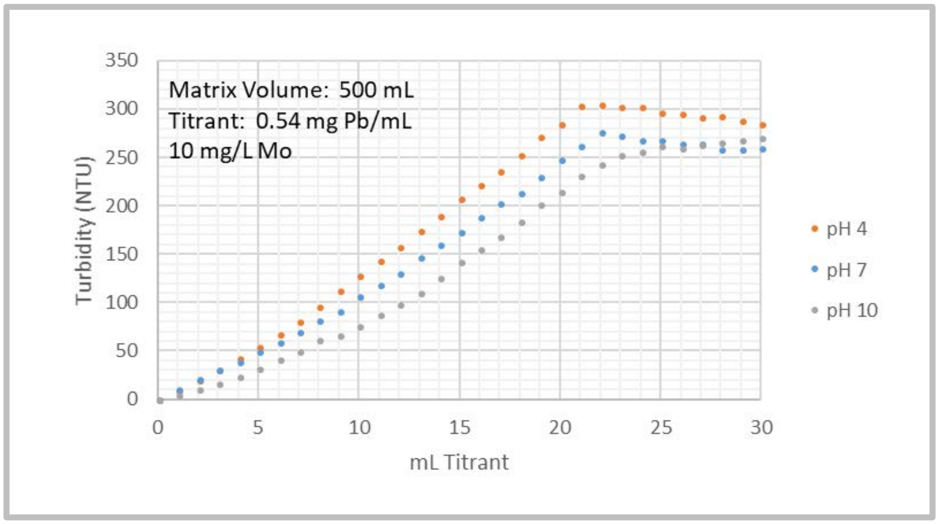

Figure 4: Titrimetric Turbidity for Lead Molybdate Precipitation

The turbidity plots provide a visual metric for determining the reagent dose needed to complete the precipitation reaction, with the reaction endpoint corresponding to the inflection point on the curve. For reference, the theoretical Pb reagent dose for a 1:1 molar ratio of Pb:Mo is 20 mL (based on 10 mg/L Mo). The experimental results are shown to be in good agreement with the theoretical reagent dose.

The apparent migration of the breakpoint to higher titrant doses as matrix pH is increased may be attributed to precipitation of lead carbonate ($PbCO_3$). Water exposed to air will uptake atmospheric carbon dioxide, which converts to carbonate as solution pH is increased. The presence of minor amounts of carbonate coupled with the low solubility product for $PbCO_3$ (Table 1: 7.40×10^{-14}) result in larger demand for Pb reagent than theoretical predictions based on stoichiometric precipitation of $PbMoO_4$.

At the completion of each precipitation experiment, the precipitant/solution matrix mixture was filtered through 0.45 µm filter paper. The filtrate was then analyzed for Mo content using a Hach DR 2700 spectrophotometer and Hach Test Method 8036 for hexavalent Mo. The filtered solids were air-dried and weighed on an analytical balance. **Table 2** contains a summary of the experimental results for the lead molybdate chemical precipitation experiments.

Table 2: Results of Lead Molybdate Precipitation Experiments

Matrix pH	Pb:Mo Molar Ratio at Endpoint	Mo in Filtrate (mg/L)	Precipitate Mass (mg)	Mass Recovery (percent)[c]
4	1.05	0.3	18 ± 2[b]	113 ± 13
7	1.10	<0.2[a]	19 ± 2[b]	119 ± 13
10	1.20	<0.2[a]	21 ± 2[b]	131 ± 13

Table 2 Footnotes:

a. The minimum detection limit for Hach Method 8036 is 0.2 mg/L as Mo.
b. The accuracy of the analytical balance used in the mass analysis is ± 1 mg per measurement. Two measurements were made for each precipitate sample.
c. The theoretical mass of lead molybdate precipitate that corresponds to 100 percent recovery is 16 mg.

The precipitate of lead molybdate is very light yellow (almost white) in color, consisting of very fine granular microcrystalline particles that require the presence of a metal coagulant (e.g. ferrihydrite) to efficiently settle. The precipitated solids remain stable (i.e. insoluble) within the pH range of 4 to 12.

The primary advantages of chemical precipitation of hexavalent Mo with Pb reagent are as follows:

- The lead molybdate precipitation process is fully compatible with the existing treatment train at the PDWTP and can be incorporated into the current treatment regimen by simple addition of Pb reagent to the process.
- Because lead molybdate is relatively insoluble in water, a stoichiometric Pb:Mo molar ratio of 1:1 can be used to effectively remove hexavalent Mo from solution. This molar ratio corresponds to a Pb:Mo mass ratio of 2.16:1. In practice, additional Pb reagent will need to be added to satisfy the chemical demand exerted by dissolved carbonates.
- The lead molybdate precipitation process may provide a means for recovery of acid soluble molybdenum generated during the milling of oxide ores at Climax. This recovery method may result in additional Mo credits for Climax.
- Based on analysis with Hach Method 8306, residual Mo concentrations below a value of 0.2 mg/L are achievable over a wide range of solution pH using soluble $PbCl_2$ salt as the reagent.
- Residual solids containing lead molybdate remain stable and insoluble within the pH range of 4 to 12.
- Lead molybdate precipitate forms dense, granular microcrystalline particles that settle rapidly in the presence of a metal coagulant, and are easily dewatered.
- When ferrihydrite precipitate is generated in the treatment process, any residual Pb that remains in solution after precipitation of hexavalent Mo could also be removed via the ferric iron co-precipitation process. Bench-scale testing is needed to confirm such a removal process for residual lead.

Some potential disadvantages of using Pb reagent for treatment of hexavalent Mo include the following:

- Lead is a contaminant listed in EPA's primary drinking water standards. Regulatory agencies and primary stakeholders may object to its use for treating of a source contributing to a drinking water supply.
- Residual concentrations of lead may require the addition of a heavy metal scavenger to the treatment train. Some examples of heavy metal scavengers that are widely used for removal of residual Pb as an insoluble precipitate include sodium hydrosulfide (NaHS) and TMT (trimercaptotriazine).

Treatment Train for Chemical Precipitation of Hexavalent Mo. The sequential unit processes required for chemical precipitation of hexavalent Mo with soluble Pb are: Pb Reagent Addition → $PbMoO_4$ Precipitation → Coagulation + Ferrihydrite Co-Precipitation → Sedimentation → Filtration. This treatment regimen is fully compatible with the existing HDS treatment process used at Climax. Lead chloride solution ($PbCl_2$) would be used as the source for soluble Pb. Metal precipitates generated by the current treatment process at the PDWTP could potentially function as the coagulant for lead molybdate particulates as well as the co-precipitation media for removal of residual Pb. Process residuals consisting of lead molybdate and ferrihydrite sludge will require dewatering using the existing filter press prior to onsite disposal.

Chemical Precipitation Residuals Management. Dewatered solids containing lead molybdate precipitate can be disposed in the existing residual storage facility at Climax along with other residual solids and tailings from milling process. The lead molybdate will remain in solid form as long as the pore water pH does not become highly acidic or highly basic.

Estimated Cost. A capital cost for implementation of a $PbCl_2$ storage and feed system is estimated to be less than $0.5 million and will depend on the storage capacity and makeup requirements that would be incorporated into a design. The annual cost for chemical reagent at $200 per metric ton of dry material would be in the range of $50,000 to $100,000 depending on the actual mass of Mo that needs to be removed and the total volume of water to be treated.

ION EXCHANGE

Selective removal of dissolved hexavalent Mo by adsorption is achievable with a molybdenum-selective ion exchange (IX) adsorptive media. For circumneutral pH conditions, a weak base anion exchange resin with quaternary amine functional groups is the preferred IX medium for adsorptive uptake of molybdate anions (e.g., Purolite Puromet MTA1011 or Dow Amberlyst A21). This resin type has an anion exchange capacity of 3.5 – 4.0 charge equivalents per liter (eq/L). Nitrate is the main competing anion with molybdate on the IX medium.

The advantage of a selective IX resin is that the capacity of the media is maximized, which is a process operating parameter important for the elevated Mo levels in Climax water. Maximizing capacity for a specific constituent improves the overall efficiency of the process, leading to lower effluent concentrations. Selectivity also increases waste management options since Mo is concentrated in the eluent (regenerant stream), where it can be managed more effectively or recovered without interference from competing constituents.

Caustic soda (NaOH) is used as the regenerant solution for loaded (pregnant) resin. High-pH spent regenerant solution (pregnant brine) is neutralized with hydrochloric acid (HCl). The eluted molybdate anions contained in the neutralized pregnant brine can be recovered as calcium molybdate precipitate by addition of calcium chloride ($CaCl_2$).

The main advantages of using ion exchange for treatment of Mo at Climax include the following:

- Selective removal of molybdate anions can be achieved with commercially available IX resins.
- The IX adsorption process is considered one of the "best available technologies" for treatment of Mo.
- Eluted Mo contained in pregnant brine can be recovered as a commercial product by addition of calcium chloride. This recovery method may result in Mo credits for Climax.

The main disadvantages of using ion exchange for treatment of Mo at Climax are as follows:

- A new treatment train consisting of IX pressure vessels loaded with Mo-selective IX resin, and resin regeneration apparatus would need to be installed at the PDWTP.
- Regeneration of IX resin is a chemical-intensive process that generates significant volumes of waste solution requiring additional treatment and disposal.

Ion Exchange Treatment Train. Implementation of an ion exchange treatment process at Climax would require installation of a separate treatment train consisting of IX columns containing Mo-selective adsorptive media. In order to minimize the Mo effluent concentration, the IX columns would need to be hydraulically configured in a lead-lag-standby series arrangement. Chemical reagents required for regeneration include caustic soda and hydrochloric acid. Recovery of Mo product from pregnant brine solution is achieved using calcium chloride.

Ion Exchange Process Residuals Management. Process residuals from the IX treatment train consist of a pH-neutralized barren brine solution containing elevated concentrations of sodium chloride and minor amounts of hexavalent Mo. The barren brine is amenable to reverse osmosis (RO) membrane treatment for volumetric reduction of process residuals and ultimate disposal at an offsite waste management facility.

Estimated Cost. The cost for Mo-selective resins are considered average (~$600 per cubic foot; Purolite) when compared to other selective resins. Based on this expected resin cost and Stantec's experience with other IX designs, the capital cost for implementation of a 14,000-gpm, Mo-selective IX WTP is estimated to be in the range of $100 million to $150 million. Operating costs cannot be estimated without pilot testing.

Prove-Out Requirements for Ion Exchange. Pilot-scale testing of Mayflower pond water would be required to support a full-scale implementation of the ion exchange process for selective Mo removal. The test protocol would be developed from manufacturer operating recommendation in addition to information that is available from ion exchange extraction work that previously occurred at Climax. The key objectives of pilot-scale testing of an ion exchange process would be removal efficiency, hydraulic loading, column configuration, resin capacity, regeneration optimization, and brine waste characterization.

ANAEROBIC MICROBIAL REDUCTION OF AQUEOUS HEXAVALENT MO

Anaerobic microbial reduction is a biological process involving anaerobic bacteria that derive energy for growth by coupling electron transport from organic matter to the reduction of oxyanions like sulfate. Recently, it has been demonstrated that anaerobic microbes known as ***sulfate reducing bacteria*** (SRBs) have a preference for metabolizing molybdate oxyanions in place of sulfate oxyanions [Shukor and Syed, 2010].

Laboratory studies conducted with SRBs indicate that reduction of molybdate by cultures of *Desulfovibrio desulfuricans* produces the sulfide mineral molybdenite, MoS_2 [Tucker et al., 1997]. Reduction of hexavalent Mo by SRBs was demonstrated to be an enzymatic process requiring viable bacterial cells plus an electron donor of either lactate or hydrogen gas (H_2). With the addition of 1-3 mM molybdate (100-300 mg/L Mo) to a culture medium containing sulfate, reduction of hexavalent Mo to insoluble quadrivalent Mo coincided with sulfate reduction and production of hydrogen sulfide (H_2S).

Although microbial reduction of hexavalent Mo by SRBs has been demonstrated in laboratory-scale benchtop experiments, full-scale treatment plants that are able to achieve sufficiently low Mo effluent concentrations are not technologically viable or commercially competitive at this time. Furthermore, successful application of a biological system under the field conditions present at Climax would require a period of significant pilot-scale testing to demonstrate that the biological reactor would perform as designed year-round. While the process might be effective, the system would need to be very large to handle the maximum flows at Climax (14,000 gpm), and the available areas at Climax are limited. Furthermore, the biological system would not be readily integrated into the existing water management or water treatment system. Because of the limitations identified, it is concluded that anaerobic microbial reduction of hexavalent Mo is a less viable water treatment option at Climax and is, therefore, excluded from further evaluation.

Prove-Out Requirements for Anaerobic Microbial Reduction. Given the stated limitations of this treatment approach, Stantec would recommend that any biological treatment testing for Mo removal be conducted at laboratory scale to determine the broad design criteria for potential implementation. Laboratory testing should provide information on required detention volume (translated to area), low temperature performance, and response to variable influent rate. This type of preliminary information should indicate if application of the technology is feasible within the site-specific constraints. If not, further testing and consideration would not be necessary. If feasible, larger-scale testing would be required, potentially implemented in stages to optimize and increase capacity to full-scale requirements.

ELECTROCOAGULATION

Electrocoagulation is an electrolytic process that generates an insoluble metal coagulant by electrodissolution of a sacrificial metal anode. In this treatment process, an electrical current is applied to a bank of metal electrodes (iron or aluminum) immersed in water that contains the targeted contaminants. The applied current induces coupled oxidation/reduction reactions between the metal electrodes and the dissolved ions [Heidmann and Calmano, 2008]. Oxidation of the metal anodes generates insoluble metal oxyhydroxides of ferric iron (FeOOH) and aluminum (AlOOH). Chemical reduction reactions result in conversion of soluble oxyanions to insoluble solid compounds.

Electrocoagulation with iron electrodes has been demonstrated to be a “best available technology” for broad spectrum treatment of metalloid oxyanions, including selenate, arsenate, and phosphate.

Unfortunately, published information is lacking on the use of electrocoagulation for removal of molybdate oxyanions. Although, the electrochemical reduction produced in this process is theoretically applicable to low aqueous Mo solubility when Mo is converted to reduced oxidation states.

Depending on the amount of applied electric current (usually dictated by level of removal needed), the process can generate a substantial amount of solid precipitate, primarily in the form of iron or aluminum oxyhydroxides released from the sacrificial anodes. The treatment train for the electrocoagulation process includes a reactor vessel where the metal electrodes are housed, followed by a clarification basin for solids settling. Clarified effluent may require filtering prior to discharge, while settled solids are typically dewatered prior to disposal. The key cost factors for electrocoagulation include electrical power consumption, frequency of metal electrode replacement, and residual solids management.

Although electrocoagulation has been successfully applied at full-scale treatment plants for electrochemical reduction of various metalloid oxyanions, Stantec is not aware of published reports that address the effectiveness of this technology for treatment of molybdate. While the technology cannot be summarily discarded from consideration, the other technologies discussed herein are all more readily implemented within the existing treatment system at Climax and offer effective treatment outcomes. Therefore, Stantec does not recommend that electrocoagulation be carried forward for further evaluation. However, electrocoagulation will be retained as a backup treatment process if the other more apparently viable water treatment options do not prove out as indicated.

Prove-Out Requirements for Electrocoagulation. Pilot-scale testing of Mayflower pond water would be required to prove out the electrocoagulation technology for Mo removal at Climax. The testing is needed to determine removal efficiency at various electrical currents, electrode consumption, solids generation rates, and solids separation criteria. A test protocol would need to be developed by Climax with input from equipment suppliers. The test protocol would need to ensure test objectives are clearly stated and that test results provide necessary information for input into required design and engineering, assuming the technology is effective.

MEMBRANE SEPARATION

Membrane separation (reverse osmosis or nanofiltration) provides physical separation of constituents (at the molecular level) and may be suitable for Climax given the potential need to reduce concentrations of multiple constituents. Multiple types of membrane elements are available in membrane separation applications that provide varying degrees of constituent removal, ranging from as low as 50 percent up to 99.9 percent or more. In terms of Mo removal (referred to as rejection in membrane separation), there is limited published data mainly because there are other more applicable and practical technologies for Mo removal. However, based on Stantec's direct experience with removal of other metals, >99.9 percent reduction in Mo should be possible with membrane separation.

The membrane separation technology produces two liquid streams: (1) a clean permeate and (2) a brine concentrate that contains the majority of dissolved ions from the feed stream. The concentration of dissolved ions in the brine typically controls the system recovery (percentage of permeate flow to influent flow) that can be achieved. This is because elevated concentrations result in oversaturated conditions that can produce mineral scales. If mineral scales form in the process, the membrane elements will foul causing increased pressure and decreased permeate production. For mining waters, the common mineral scalants are metals, sulfate, and silica. The use of antiscalants increases the effective saturation levels of mineral scalants and can increase the overall recovery achievable. Higher recoveries are desired because of associated lower volumes of brine concentrate that need to be managed as a waste or side stream.

If membrane separation is applied to the Mayflower Pond water, a system recovery of 60 to 80 percent might be expected, based on a limited review of available water quality. Although the resulting discharge water quality would be the highest of any technology applicable to Climax, approximately 20 to 40 percent of the influent stream would require post treatment management. Accumulation of brine solution would be problematic as the dissolved constituent concentrations increase over time, requiring the implementation of another waste management measure.

Membrane separation is an advanced technology that typically costs more to implement than conventional technologies. Although the capital cost will highly depend on the ancillary system requirements, Stantec's experience is that a membrane separation WTP will cost between $10 million and $15 million per 1,000 gpm of feed capacity. This means that a membrane separation system implemented at the PDWTP would likely cost in the $140 million to $210 million range (assumes 14,000 gpm capacity). Considering that other Mo removal technologies will be as effective as membrane separation, Stantec does not recommend further pursuit of this technology unless a broad spectrum of constituent removal is needed.

Prove-Out Requirements for Membrane Separation. Other than cost, the key limitation for membrane separation at Climax is the large amount of brine concentrate that is expected to be generated. Based on this limitation, testing of the membrane separation technology should begin at the laboratory scale to determine the actual recovery that can be consistently achieved. Once the recovery is determined, the volume of brine concentrate that would require management could be calculated. Climax would then need to evaluate the possibility of managing the brine on site to determine if the membrane separation technology is feasible within the site constraints. If determined feasible, then pilot-scale testing would be required to fully prove out this technology for possible implementation.

EVALUATION SUMMARY

Stantec has evaluated six alternative technologies that are applicable for removal of Mo from the Climax water system. The results of the evaluation are summarized in the following:

- Chemical precipitation of Mo with Pb forming the solid $PbMoO_4$ appears to be the most cost-effective alternative technology for Mo reduction. As this method is not a conventional treatment process, Stantec recommends testing to determine the efficiency of the removal using actual mine water as well as characterization of the solids that result. Additional consideration is also needed regarding use of Pb as a reagent and what additional treatment might be needed to address residual Pb.

- In the opinion of Stantec, adsorption of Mo with ferric iron is the base case technology as it is already implemented at multiple locations and performance of the technology is established.

- Anaerobic biological treatment is not well-suited for the climate or available area at Climax and does not provide precedent for successful application for Mo removal. Other technologies evaluated are more practical and likely to produce lower Mo concentrations in a more efficient manner.

- Similar to biological treatment, electrocoagulation is less practical than other chemical precipitation processes and would be expected to produce larger amounts of solid waste. Thus, this technology is not recommended for further evaluation unless all other technologies are deemed infeasible.

- Membrane separation and IX are effective for Mo removal, but are also likely to be the least efficient in terms of waste generation. Additionally, implementation of either of these technologies will likely have a higher cost than a co-precipitation or chemical precipitation system. Further evaluation of membrane separation is warranted if additional constituents of concern need to be addressed.

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APPENDIX C

Option 9 – Build Molybdenum Treatment Plant

Appendix C Option 9– Build Molybdenum Treatment Plant

C.1 BUILDOUT OF THE MO REMOVAL PLANT

C.1.1 Option Description

The buildout of the Mo Removal Plant at the PDWTP is the baseline option for the Climax Mine to reduce Mo concentrations in the site discharge.

The Mo Removal Plant design consists of Reactors, Clarifiers, Filters, Solids Dewatering, and Chemical Feed systems. The Reactors are acid resistant to protect equipment in the pH 4.5 operating condition. The acidic pH in the Reactors is established by the acidity of the ferric sulfate that is dosed into the process for Mo removal. Lime slurry is added to ensure the optimum pH is attained.

Suspended solids generated in the process are separated in two steps, conventional clarification followed by media filtration. The pH 4.5 operating condition is maintained throughout the solids separation steps to ensure Mo adsorption to the ferric iron solids is not reversed. The filtrate from the media filters is pumped to the Metals Removal Plant for treatment of metals that are not removed in the Mo Removal Plant. Solids generated by the Mo Removal Plant are conditioned with flocculant and dewatered prior to on-site disposal.

C.1.2 Capital Expenditure

The Capital Expenditure estimate was prepared by Golder in 2017, totaling $75,073,000 for the Mo Removal Plant. The Capital estimate includes installation of all equipment required for the process described above, an insulated and heated building to house all of the equipment, and chemical storage and feed systems. A summary of the 2017 Golder capital cost estimate is provided in **Table C-1**. For purposes of the cost comparison for the SBP, Stantec will use the cost estimate provided by Golder that escalates the 2017 cost estimate to July 2019 dollars, for a total capital cost estimate of $79,652,000.

Table C-1. Option 9 Capital Cost Estimate Summary

Mo Removal Plant (14,500 gpm) - Capital Cost Estimate		
Cost Item		**Cost**
Labor		$12,111,000
Materials		$13,868,000
Subcontractor		$13,562,000
Equipment		$3,018,000
	Subtotal	***$42,559,000***
Material Sales and Use Tax		$940,000
Construction Equipment Tax		$212,000
	Subtotal	***$1,182,000***
Owner Furnished Items		$11,995,000
Tax on Owner Furnished Items		$836,000
	Subtotal	***$12,791,000***
Contingency		$8,463,000
	Subtotal	***$8,463,000***
Construction Management		$3,669,000
Engineering/SDCs/Commission		$5,534,000
	Subtotal	***$9,203,000***
Owners Cost		$5,454,000
Total		**$79,652,000**

C.1.3 Operation Costs

The operating cost estimate was also prepared by Golder in 2017 and includes chemical consumption, electrical, heating, and operational labor. The operating estimate prepared by Golder totals $2,665,000 annually, and $2,829,000 escalated to July 2019 dollars. A summary of the 2017 Golder operation cost estimate is provided in **Table C-2**.

Table C-2. Option 9 Annual Operation Cost Estimate Summary

Mo Removal Plant (14,500 gpm) - Operation Cost Estimate	
Cost Item	**Cost**
Facility General Maintenance	$836,000
Chemical	$1,339,000
Electrical	$181,000
Operations Staff	$411,000
Sludge Hauling	$47,000
Laboratory Analysis	$15,000
Total	**$2,829,000**

APPENDIX D

Option 10a/b – Modify Existing Water Treatment Facilities with No Change in Water Management

Appendix D Option 10A/B - Modify Existing Water Treatment Facilities with No Change in Water Management

D.1 FERRIHYDRITE CO-PRECIPITATION PROCESS

D.1.1 Option Description

The purpose of Options 10a and 10b is to present possible modifications to the existing SDP and PDWTP facilities without modifying the current water management system.

This section describes the cost basis for implementing potential process modifications at the Climax Property Discharge Water Treatment Plant (PDWTP) under Option 10a. The proposed changes are primarily intended for treatment of molybdenum (Mo), which is not currently optimized under the existing processes utilized at the PDWTP. This option focuses on changes to the PDWTP chemical treatment process, and only considers the process optimization involving co-precipitation of soluble Mo with ferric iron (as ferrihydrite) and precipitation of manganese (Mn) via oxidation with potassium permanganate (KMnO4).

In Stantec’s opinion, SDP would not require modification to be able to operate at a pH of 10 so no modifications have been costed out for the facility.

At the PDWTP, Reactor No. 1 would be operated per the current configuration for metals removal prior to the removal of Mo. To meet the new process intent in the PDWTP, modifications start at Reactor 2 where a metered feed of ferric sulfate (58 percent by weight) would be added to promote the co-precipitation of the molybdenum (Mo) which would decrease the pH between 4.5 and 5 during normal operation. An additional feed of potassium permanganate would also be introduced to Reactor 2 for removal of manganese (Mn) if the Reactor 1 pH was not high enough for complete oxidation of Mn with air. The Reactor 1 pH level would be set so that the Reactor 2 pH falls in the optimum pH target range after addition of ferric sulfate. Overflow from Reactor 2 would follow the current flow path to the launder and splitter box where the new flocculant would be added by a weighted feeder. Physical separation of the precipitated solids from the Reactor effluents would occur in the thickeners. Discharge from the thickeners would be neutralized to a pH of 7 before reporting to the filtration building.

D.1.2 Capital Expenditure

The current system was constructed using mild steel components intended for operation at pH 10, with the exception of some stainless-steel valving and agitators. To meet the new low-pH process requirements, all mild steel and wetted concrete surfaces would need to be replaced or lined for compatibility. No modifications to the current structural design are considered necessary for the conversion to a low-pH condition. The cost estimation for this option includes the lining of the two reactor tanks, the two thickeners, and the metal sludge recycle and waste circuits.

To minimize the impact to the existing facility, major tanks would be left in place and would be coated with acid-resistant, 175 mil polyurea liner. The affected surface area has been calculated based on mechanical drawings of the tanks and overall facility. Tank surface areas include internal accessories such as baffles and air bubblers. Structural steel above the tanks and supporting the tanks are included in the surface area calculations for the lining. Grating would be replaced with composite fiberglass as lining these features would be time consuming and unreliable.

Affected piping would be replaced with HDPE piping with the boundary limit defined by the discharge of the thickeners. Valves would be replaced with lined valves except for the Pinch valves, located underneath the thickeners, which are only expected to require a liner replacement after discussion with the manufacturer. Current actuators for the valves would be reused and mounted onto the new valves. Specific concrete areas are also identified for lining, including the two thickener underflow areas, affected tank bases, and the sump. Additional milk of lime feed lines would be routed to the thickener discharge boxes to neutralize the treated water before being routed to the filtration building. Agitators would also be placed in this box to enhance mixing.

In addition to the acid-resistant conversion inside of the PDWTP, an additional set of reagents would be required for this water treatment process. This has been approached by adding a reagent building immediately next to the existing road area. This building has been sized at 30’ x 56’ and would contain two 14’ D x 12’ H ferric sulfate tanks which would be housed in their own containment within the building. One of two new pumps would transfer the ferric sulfate to a day tank located within the PDWTP on the upper deck. The remainder of the building would be designed for dry reagent storage laydown for supersacks of potassium permanganate and pallets of flocculant while maintaining an open area for forklift access. Bag breakers and feeders would be placed within the PDWTP and reagent lifted to the point of application by auger feeders.

Surface coatings, pumps, valving have all been quoted by local vendors. For equipment of the same size as equipment quoted in the past year, historical information is used. Building cost was obtained from R.S Means 2018 median cost information for a PEMB based on the sizing. Concrete and earthwork were estimated based on local ground work requirements only at recent contractor rates from 2018. Equipment installation, project ancillaries, and piping costs were factored according to industry standard methods.

All indirect costs of the project were estimated within industry standard ranges for factors. Engineering and construction management costs were assigned at the lower end of the industry range. Industry Freight, equipment rental, consumables, startup, mobilization, and project insurances were quoted at the mid-range given the size of the project.

The expected capital expenditure of Option 10a is $26,202,000 USD. The summary of the cost makeup is included in **Table D-1**.

This cost is presented with 6.99% taxes on Materials and Rentals, a 40% contingency, and an 8.8% Owner’s cost. Construction Management costs are estimated at 8%. Engineering Costs are presented including a 5% factor of capital (based on the large project size), and a flat rate of $250,000.

Table D-1. Option 10a Capital Cost Estimate Summary

Mo Removal Plant (14,500 gpm) - Capital Cost Estimate			
Cost Item		**Cost Factor**	**Cost**
Labor			$6,100,495
Materials			$2,308,991
Subcontractor			$2,843,043
Equipment			$3,924,755
	Subtotal		**$15,177,284**
Material Sales and Use Tax		6.99%	$161,398
Construction Equipment Tax		6.99%	$274,340
	Subtotal		**$435,739**
Contingency		40%	$6,245,209
	Subtotal		**$6,245,209**
Construction Management		8%	$1,215,000
Engineering/SDCs/Commission			$1,009,000
	Subtotal		**$2,224,000**
Owners Cost		8.8%	$2,119,236
Total			**$26,201,468**

D.1.3 Operation Costs

The ferrihydrite process uses three new reagents at the PDWTP: ferric sulfate, Magnafloc® 155, and potassium permanganate. There is also an increase in the use of lime, which is already delivered to the site and is slaked on site. Because a slaking facility already exists, anhydrous lime has been included as the primary base reagent. All new reagents were quoted by vendors for this project at FOB costs. Lime costs and shipping is based on historical quotes received. Stantec assumed that this additional hardware would be sufficiently automated to not require additional operations personnel.

Electricity is estimated for the new equipment after power factor considerations at $0.15/kWh.

Given the extensive lining performed for this option, quarterly inspections of the lining are included. This is currently estimated based on a team of four third-party liner inspection technicians for one week, four times per year.

The annual estimated additional operating costs for Option 10a is $615,325 USD. Rates assume three months of snowmelt operation and nine months at nominal conditions. Usage rates and itemized costs are included in **Table D-2**. This assumes that the operation of the facility will not need additional personnel.

Table D-2. Option 10a Operating Cost Estimate Summary

Ferrihydrite Process - Operating Cost						
Reagent Costs						
ITEM	**Usage lb/day**	**Weekly Usage**	**Cost US$/lb**	**Delivery to Site**	**Cost to Site**	**2019 Cost**
Anhydrous Lime	877	6,139.00	$0.20	$0.04	$0.24	$76,615
Ferric Sulfate (58%)	1216	8,510.25	$0.58	$0.02	$0.60	$266,995
Magna Floc 155	210	1,470.88	$1.38	$0.20	$1.58	$121,113
Potassium Permanganate	236	1,651.30	$2.84	$0.94	$3.78	$324,580
Total Reagent Costs						**$464,722**
Energy Costs						
ITEM				**$/kWh**	**Total kW**	**2019 Cost**
Electricity				0.15	20	$26,603
Maintenance						
ITEM	**Qty**	**Days**	**Daily Rate**	**Frequency**	**Trip Cost**	**2019 Cost**
Liner Inspection	4	5	1500	4.00	250	$124,000
Total Annual Cost						**$ 615,325**

D.2 OPTION 10B – LEAD MOLYBDATE PROCESS

D.2.1 Option Description

This section describes the cost basis for implementing potential process modifications, as Option 10b, at the Climax Property Discharge Water Treatment Plant (PDWTP) for Mo removal by precipitation of lead molybdate by addition of lead chloride ($PbCl_2$). This proposed option focuses on changes to the PDWTP chemical treatment process, and only considers the process optimization involving chemical precipitation of soluble Mo as lead molybdate ($PbMoO_4$), potential precipitation of Mn with potassium permanganate ($KMnO_4$), and potential sulfide reagent polishing of residual lead (and potentially Cd) concentrations. This process also requires addition of ferric sulfate to assist with coagulation of the lead molybdate precipitant, and could potentially further reduce the residual concentration of molybdenum.

This process involves operation of the reactor precipitation circuit at a pH of 7.5 controlled by addition of lime using the existing system. The $PbCl_2$ is added as a solid in Reactor 1 to precipitate Mo and provide necessary residence time through both reactors. Potassium permanganate is added to Reactor 2, to target remaining Mn in the water. Polymer (i.e., flocculant) addition to the splitter box is equivalent to Option 10a. The sulfide addition occurs in the splitter box to scavenge residual lead as described previously. At present, an organosulfide reagent is suggested to avoid the need for management of inorganic sulfide. The primary benefit of Option 10b is that major modification to the existing PDWTP is not required.

D.2.2 Capital Expenditure

As a result of targeting a circumneutral pH of 7.5 pH, major modification of the existing PDWTP is not required. The current system has been largely designed from mild steel which is considered acceptable for the proposed neutral pH service. The implementation of this option will require reagent line additions to the existing process as well as more reagent equipment.

The reagent building described previously for Option 10a is also acceptable for the Option 10b reagent additions to the facility. There are two additional reagents for Option 10b (relative to Option 10a): organosulfide and $PbCl_2$. The organosulfide containers will be located within the reagent building. Lead chloride would be stored in a silo adjacent to the plant-southwest wall of the PDWTP to be near the point of use. Tanks and silos are sized for one week plus one shipment to the nearest standard tank sizing.

Tank and silo costs are based on similar service of equivalent size from quotes received in the past year. Pumps and valves are based on vendor quotations in the local area. For equipment of the same size as equipment quoted in the past year, historical information is used. Building cost is estimated using R.S Means 2018 median cost information for a PEMB based on the sizing. Concrete and earthwork are estimates based on local ground work requirements only at recent contractor rates from 2018. Equipment installation, project ancillaries, and piping costs are factored according to industry standard methods.

All indirect costs of the project are estimated within industry standard ranges for factors. Engineering and construction management costs are estimated toward the median-high of the industry range given the small size of the project. Industry freight, equipment rental, consumables, startup, mobilization, and project insurances are quoted at the high-range given the size of the project.

The estimated capital expenditure of Option 10b is $3,600,000 USD. All equipment considerations, and final factors are presented in **Table D-3**.

This cost is presented with 6.99% taxes on Materials and Rentals, a 40% contingency, and an 8.8% Owner’s cost. Construction Management costs are estimated at 8%. Engineering Costs are presented including a 5% factor of capital (based on the large project size), and a flat rate of $220,000.

Table D-3. Option 10b Capital Cost Estimate Summary

Mo Removal Plant (14,500 gpm) - Capital Cost Estimate		
Cost Item	**Cost Factor**	**Cost**
Labor		$343,032
Materials		$352,128
Subcontractor		$446,461
Equipment		$700,030
	Subtotal	**$1,841,651**
Material Sales and Use Tax	6.99%	$24,614
Construction Equipment Tax	6.99%	$48,932
	Subtotal	**$73,546**
Contingency	40%	$766,079
	Subtotal	**$766,079**
Construction Management	10%	$185,000
Engineering/SDCs/Commission		$405,000
	Subtotal	**$590,000**
Owners Cost	8.8%	$287,872
Total		**$3,559,148**

D.2.3 Operation Costs

The lead molybdate process introduces five new reagents at the PDWTP: ferric sulfate, Magnafloc® 155, lead chloride, organosulfide, and potassium permanganate. There is also an increase in the use of lime, which is already delivered to the site and is slaked locally. Because a slaking facility already exists, anhydrous lime has been included as the primary caustic reagent. All new reagents were quoted by vendors for this project at FOB costs. Lime costs and shipping is based on historical quotes. Stantec assumed that the existing staff will be able to include this approach into the normal operation of the plant without additional workforce.

Electricity is estimated for the new equipment after power factor considerations at $0.15/kWh.

The annual operating costs of the Option 10b lead molybdate process are estimated at $1,700,000 USD. Rates assume three months of snowmelt operation and nine months at nominal conditions. Stantec assumed that additional operations and maintenance staff would not be required for this option. Usage rates and itemized costs are included in **Table D-4**.

Table D-4. Option 10b Operating Cost Estimate Summary

Lead Molybdate Process - Operating Cost						
Reagent Costs						
ITEM	**Usage lb/day**	**Weekly Usage**	**Cost (FOB) US$/lb**	**Delivery to Site**	**Cost to Site**	**2019 Cost**
Anhydrous Lime	1,635.9	11,451	$0.05	$0.12	$0.17	$101,231
Ferric Sulfate (60%)	2,635.3	18,447	$0.58	$0.02	$0.60	$578,736
Magna Floc 155	147.1	1,029	$1.38	$0.10	$1.48	$79,405
Organosulfide	43.0	301	$14.29	$0.20	$14.49	$226,857
Potassium Permanganate	235.9	1,651	$2.84	$0.94	$3.78	$324,778
Lead Chloride	150.3	1,052	$5.88	$0.20	$6.08	$332,746
Total Reagent Costs						**$1,643,752**
Energy Costs						
ITEM				**$/kWh**	**Total kW**	**2019 Cost**
Electricity				0.15	21	$27,923
Total Annual Cost						**$ 1,671,675**

D.3 OPTION 10 SUPPORTING DOCUMENTATION

The new reagent building would be required for both Option 10 approaches. Located on the east side on the plant, the reagent building optimizes the current traffic routing corridors for trucks and proximity to support the PDWTP. The ferric sulfate tanks would be in the southeast section of the new reagent building with the remainder of the area allocated for dry reagent storage laydown of potassium permanganate and flocculant. The organosulfide reagent drums could be housed in the northeast section of the building for Option 10b. Probable locations of new reagent handling equipment for each option are also identified as part of the attached drawing 233001306 - GA-01- Molybdenum Treatment Alternatives Evaluation General Arrangement.

An equipment summary list, as well as preliminary sizing for the Option 10a and 10b approaches, is also attached. Each list is designed on the basis outlined previously. Notes on items related to cost development are outlined in the comments column along with pricing used for the cost estimates. See attachments for complete details.

Given the extensive work involved with the coating operation, the existing equipment mechanical drawings were used to calculate the surface area for coverage. These calculations and coordination with the lining polymer supplier were used to develop the current summary of the required areas and equipment for coverage. These calculations are included in the attachments to **Appendix D**.

REV	DATE	BY	DESCRIPTION
A	2/28/2019	DG	ISSUED FOR INFORMATION

SCALE
1" = 500'

WARNING
0 ½ 1
IF THIS BAR DOES NOT MEASURE 1" THEN DRAWING IS NOT TO SCALE

DESIGNED D.GRILLS
DRAWN J.RICKS
CHECKED D.DUPON

Climax Molybdenum
A Freeport-McMoRan Company

Stantec

DRAWING TYPE
GENERAL ARRANGEMENT CONCEPT

MOLYBDENUM WATER TREATMENT ALTERNATIVES EVALUATION
PDWTP
OPTION 10

SHEET
GA-01
233001306

Friday, March 1, 2019 9:49:27 AM \\US0325-PPFSS01\WORKGROUP\2330\ACTIVE\233001306\05_REPORT\COST ESTIMATE\GENERAL ARRANGEMENT\PDWTP-GA.DWG RICKS, JENSEN

Client:	Climax Molybdenum
Project:	Climax PDWTP Process Refit
Project #:	233001306
Revision:	A
Date	3/11/2019

Equipment Surface Area Calculations - Tanks and Supports

Global Factors		
Coating Waste	10%	

Launder and Splitter Box					**Notes**
Internal Surfaces and Supports					Dimensions Based on 05 12 00-005A (Vendor Drawing Rocky Mountain Steel, E400)
Launder Length	50.7	ft			
Launder Start Height	7.9	ft			
Launder End Height	10.4	ft			
Launder Width	2.80	ft			
Launder Bottom Θ	2.98	deg	0.052	rad	
Launder Bottom Area	142.2	ft2			
Launder Sides	864.2	ft2			
Launder End Area	29.2	ft2			
Splitter Box Height	12.5	ft			
Splitter Box Width	10.8	ft			
Splitter Box Length	9.9	ft			
Box Internal Area	623.1	ft2			
Splitter Box Baffles	514.3	ft2			
Steel Beam Area/L	3.1	ft2/lf			W8X21 Beam Dimensions Used
Length of Beams	290.5	lf			
Beam Area	911.1	ft2			
Box Lip Area	55.2	ft2			
Launder Lip Area	201.8	ft2			
Pipe Flange Diameter	3.5	ft			
Pipe Flange Area	84.0	ft2			
Launder Beams	556.0	lf			
Launder Support Area	1744.1	ft2			
Lateral Structural Support (Type 1)	8.4	ft2/lf			W24X131 Beam Dimensions Used
Lateral Support Length (Type 1)	217.8	lf			6 feet added on either side of the full beam length for splash area.
	1822.0	ft2			
Lateral Structural Support (Type 2)	6.9	ft2/lf			W18X106 Beam Dimensions Used
Lateral Support Length (Type 1)	91.1	lf			Under Splitter Box Only, 6 feet added on each side for splash area
	624.4	ft2			
Total Internal and Support Area	8377.3	ft2			
External Surfaces					
Launder External Area	1035.6	ft2			
Splitter Box External Area	623.1	ft2			
Total External Surface Area	1824.6	ft2			

Metals Reactor Tank No. 1 (840-TK-002)			**Notes**
Internal Surfaces and Supports			Dimensions Based on drawing SK-840-TK-002, Rev 1
Tank Diameter	31	ft	
Tank Height	36	ft	
Tank Surface Area	7,012	ft2	
Baffles	4		
Baffle Height	32.417	ft	
Baffle Width	2.5	ft	
Supports per baffle	9		
Support Surface Area	8	ft2/lf	4" angle Iron Considered for Area
Total Baffle Surface Area	936	ft2/lf	
Air Sparger Diameter	4.5	ft	
Air Sparger Height	5	ft	
"Bottle Cap" Diameter	6.16666667	ft	
	219	ft2	
Downcomer Diameter	3.5	ft	
Downcomer Height	6	ft	
Downcomer Surface Area	33.0	ft2	
Upcomer Diameter	3.5	ft	Half plat welded to wall
Upcomer Height	30.25	ft	
Upcomer Surface Area	166.3	ft2	
Overflow Box Width	6		
Overflow Box Depth	2		
Overflow Box Height	2.6		
Overflow Drain Pipes	0.75		9". Cut pipes to ground and weld ANSI 150 Flange. Connect to HDPE Piping routed to ground trench
	65	ft2	
Total Surface Area	9,274	ft2	

840-TK-003	Metals Reactor Tank No. 2, Duplicate Tank.		**Notes**
Total Surface Area	9,274	ft2	Typical Tank Configuration except same size nozzle in different location

840-TK-004	Metal Sludge Tank		**Notes**
Tank Diameter	8.5	ft	
Tank Height	12	ft	
Tank Surface Area	**641**		
Number of Baffles	4		
Baffle Height	9.2	ft	
Baffle Width	0.7	ft	
Supports per baffle	8		
Support Surface Area	2	ft2	
Total Surface Area	**416**		
Agitator Support Length	25	ft	
Beam surface Area	3.1	ft2/lf	
Total Structural Steel Area	**77**		
Total Surface Area	**1141**		

840-TK-007	Metal Sludge Tank		**Notes**
Tank Diameter	15	ft	
Tank Height	26	ft	
Tank Surface Area	**2450**		
Number of Baffles	4		
Baffle Height	25	ft	
Baffle Width	1.7	ft	
Supports per baffle	7		
Support Surface Area	1.3	ft2/lf	
	343		
Total Surface Area	**3072**		

Client:	Climax Molybdenum
Project:	Climax PDWTP Process Refit
Project #:	233001306
Revision:	A
Date	3/11/2019

Equipment Surface Area Calculations - Thickeners

21625A-1008	Concrete-Tank (840-TH-005)		
Tank Diameter	140	ft	
Tank Inside Height	15	ft	
Tank Lip Height	2.28125	ft	
Tank Height	17.28125	ft	
Launder Depth	2.5	ft	
Launder Height	2	ft	
Sidewall Coating Area	**14,575**	ft2	
Cone (1/12") diameter Start	140	ft	
Cone (1/12") diameter End	60	ft	
Actual Height	6.7	ft	
Projected Height	11.7	ft	
Area Cone Section (1/12" slope)	**25,306**	ft2	
Cone (3/12") diameter Start	60	ft	
Cone (3/12") diameter End	16	ft	
Actual Height	3.7	ft	
Projected Height	5.0	ft	
Area Cone Section (3/12" slope)	**5,289**	ft2	
Cone (6/12") diameter Start	16	ft	
Cone (6/12") diameter End	12	ft	
Actual Height	0.3	ft	
Projected Height	1.3	ft	
Area Cone Section (6/12" slope)	**177**	ft2	
Sludge Collection Box Height	12.5	ft	
Sludge Collection Box Diameter	28.1	ft	
Sludge Collection Box Outside Height	14.75	ft	
Sludge Collection Box Outside Diameter	30.1	ft	
Sludge Collection Box Inside Area	**1723.6**	ft2	
Sludge Collection Box Outside Area	**2106.4**	ft2	
Sludge Collection Box Roof Area	**645.3**	ft2	
Deck Structural Steel Length	484	lf	
Lateral Structural Support (Type 2)	6.9	ft2/lf	W18X106 Beam Dimensions Used
Structural Support Surface Area	**3,650**	ft2	
Total Thickener Surface Area	**54,805**	ft2	

Notes: These drawings do not have a lot of dimensions included with them

21625A-1009 (840-TH-006)			
Structural Support Surface Area	**3,650**	ft2	Typical of 840-TH-005
Total Thickener Surface Area	**54,805**	ft2	Typical of 840-TH-005

21625A-1008	Thickener Rake Surface Estimate (840-TH-005)		
Rake Surface Area	7,344	ft2	Assumed based on structural beam assembly of rake, W1

21625A-1008	**Thickener Rake Surface Estimate (840-TH-005)**		
Rake Surface Area	**7,344**	ft2	Typical of 840-TH-005

Client: Climax Molybdenum
Project: Climax PDWTP Process Refit
Project #: 233001306
Revision: A

MECHANICAL EQUIPMENT LIST - Climax Molybdenum - OPTION 10A

Equipment Number	Equipment Name	Approximate Dimensions	Capacity (English)	Design Pressure (atm) and Temp (°C)	Qty.	Unit HP	Operating HP	Vendor Quote/Date	Total Cost ($)
Acid Protected Equipment									
840-TK-002	Reactor No 1 Coating	31' Dia x 36' H	Existing	Existing	9,274			$35 per sq ft quoted by Custom Linings 2/1	$ 324,590
840-TK-003	Reactor No. 2 Coating	31' Dia x 36' H	Existing	Existing	9,274			$35 per sq ft quoted by Custom Linings 2/1	$ 324,590
840-TK-004	Metals Mix Recycle Tank Coating	8.5' Dia x 12' H	Existing	Existing	1,141			$35 per sq ft quoted by Custom Linings 2/1	$ 39,935
840-SB-001	Splitter Box and Launder Coating	10.8' x 10 ' box, 50' L launder	Existing	Existing	10,201			$35 per sq ft quoted by Custom Linings 2/1	$ 357,035
840-TH-005	Thickener No. 1 Coating	140' Dia x 15' Wall, cone base	Existing	Existing	58,454			$35 per sq ft quoted by Custom Linings 2/1	$ 2,045,890
	Thickener No. 1 Rake Coating	Assumed	Existing	Existing	7,344	Existing	Existing	$35 per sq ft quoted by Custom Linings 2/1	$ 257,040
840-TH-006	Thickener No. 2 Coating	140' Dia x 15' Wall, cone base	Existing	Existing	58,454			$35 per sq ft quoted by Custom Linings 2/1	$ 2,045,890
	Thickener No. 1 Rake Coating	Assumed	Existing	Existing	7,344	Existing	Existing	$35 per sq ft quoted by Custom Linings 2/1	$ 257,040
840-TK-007	Metal Sludge Waste Tank Coating	15' Dia x 26 ' H	Existing	Existing	3,072			$35 per sq ft quoted by Custom Linings 2/1	$ 107,520
	Sump Containment Coating	40' x 40' x 8'	Existing	Existing	2,880			$35 per sq ft quoted by Custom Linings 2/1	$ 100,800
						0	**0.0**		**$ 5,860,330**
Replaced Equipment									
840-PU-005C/D	Thickener No. 1 Recyce Underflow Pumps	1780 RPM	389 gpm	65' TDH, 60 °F	2	50	37.5	Denver Industrial Pump 3-1-2019	$ 49,540
840-PU-005A/B	Thickener No. 1 Waste Underflow Pumps	1780 RPM	39 gpm	45' TDH, 60 °F	2	5	3.8	Denver Industrial Pump 3-1-2019	$ 32,188
840-PU-006C/D	Thickener No. 2 Recyce Underflow Pumps	1780 RPM	389 gpm	65' TDH, 60 °F	2	50	37.5	Denver Industrial Pump 3-1-2019	$ 49,540
840-PU-006A/B	Thickener No. 2 Waste Underflow Pumps	1780 RPM	39 gpm	45' TDH, 60 °F	2	5	3.8	Denver Industrial Pump 3-1-2019	$ 32,188
840-PU-007A/B	Metal Sludge Waste Pumps	1800 RPM	471 gpm	100 psi, 60 °F	2	30	22.5	Changed from 75 HP to 30 HP, Filter Press not in use, Denver Industrial Pump 3-1-2019	$ 24,770
840-AG-002	Reactor No 1 Agitator	Dual Prop, 9' Dia. 1200 RPM			1	0	0.0	Stainless Steel from inspeciton, Not Replaced	
840-AG-003	Reactor No. 2 Agitator	Dual Prop, 9' Dia. 1200 RPM			1	0	0.0	Stainless Steel from inspeciton, Not Replaced	
840-AG-004	Metals Mix Recycle Tank Agitator	Single Prop, 2.5' Dia, 1800 RPM			1	0	0.0	Stainless Steel from inspeciton, Not Replaced	
840-AG-007	Metals Sludge Tank Agitator	Single Prop, 6' Dia, 1800 RPM			1	0	0.0	Stainless Steel from inspeciton, Not Replaced	
086, 087,090	42" Butterfly Valve				3			Rampart Supply Budgetary Quote 2/19/2019	$ 67,275.00
082, 083	36" Butterfly Valve				2			Rampart Supply Budgetary Quote 2/19/2019	$ 45,225
	6" Butterfly Valve				2			Rampart Supply Budgetary Quote 2/22/2019	$ 1,445
	30" Gate Valves				4			Rampart Supply Budgetary Quote 2/19/2019	$ 30,000.00
	12" Gate Valve				2			Rampart Supply Budgetary Quote 2/19/2019	$ 7,250
	10" Gate Valve				12			Rampart Supply Budgetary Quote 2/19/2019	$ 4,920
	1" Ball Valves				24			Rampart Supply Budgetary Quote 2/19/2019	$ 197
	3/4" Ball Valves				12			Rampart Supply Budgetary Quote 2/19/2019	$ 133
	6" Ball Valve				2			Rampart Supply Budgetary Quote 2/19/2019	$ 2,065.00
	6" Knife Gate Valve				12			Rampart Supply Budgetary Quote 2/19/2019	$ 3,595.00
	3" Check Valve				4			Rampart Supply Budgetary Quote 2/19/2019	$ 688.00
	6" Check Valve				4			Rampart Supply Budgetary Quote 2/19/2019	$ 2,155.00
	6" Magnetic Flow Meter (Replace with Open				2			Assumed	$ 8,000.00
	6" Density Meter				2			Assumed	$ 11,500.00
	3" Pinch Valve				4			Rampart Supply Budgetary Quote for FLOWROX Valves 3/1/2019	$ 1,876.25
	3" Pinch Valve - Motor Actuated				4			Rampart Supply Budgetary Quote for FLOWROX Valves 3/1/2019	$ 4,100.00
	4" Pinch Valve - Motor Actuated				4			Rampart Supply Budgetary Quote for FLOWROX Valves 3/1/2019	$ 4,130.63
	6" Pinch Valve				4			Rampart Supply Budgetary Quote for FLOWROX Valves 3/1/2019	$ 2,750.00
	6" Pinch Valve - Motor Actuated				4			Rampart Supply Budgetary Quote for FLOWROX Valves 3/1/2019	$ 5,331.25
	8" Pinch Valve - Motor Actuated				4			Rampart Supply Budgetary Quote for FLOWROX Valves 3/1/2019	$ 5,893.75
	10" Pinch Valve				8			Rampart Supply Budgetary Quote for FLOWROX Valves 3/1/2019	$ 8,234.38
						0	**0.0**	*Existing Equipment, No additional Electrical Load*	**$ 1,131,326**
Infrastructure and Safety									
840-SS-009/10/11	Reactor Area Safety Showers	2' base	20 gpm		3	0	-	Grainger combination Eyewash and Shower	$ 2,000
	Reagent Building Safety Shower	2' base	20 gpm		1	0	-	Grainger combination Eyewash and Shower	$ 2,000
	Deck Grating Replacement Reactor Area	8,760 sq ft, 2" thick			8760		-	Grainger grate replace $1,431.70/48 sq ft.	$ 261,285

Client: Climax Molybdenum
Project: Climax PDWTP Process Refit
Project #: 233001306
Revision: A

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MECHANICAL EQUIPMENT LIST - Climax Molybdenum - OPTION 10A

Equipment Number	Equipment Name	Approximate Dimensions	Capacity (English)	Design Pressure (atm) and Temp (°C)	Qty.	Unit HP	Operating HP	Vendor Quote/Date	Total Cost ($)
	Deck Grating Replacement Stairs	210 sq ft, 2" thick			210		-	Grainger grate replace $1,431.70/48 sq ft.	$ 6,264
	Thickener No. 1 Cone Area Concrete Lining	1900 Sq Ft			1900		-	$35 per sq ft quoted by Custom Linings 2/1	$ 66,500.00
	Thickener No. 2 Cone Area Concrete Lining	1900 Sq Ft			1900		-	$35 per sq ft quoted by Custom Linings 2/1	$ 66,500.00
	Metal Sludge Waste Tank Area Concrete Lining	353 Sq Ft			353		-	$35 per sq ft quoted by Custom Linings 2/1	$ 12,355.00
	Structural Steel Coating (Reactor Area)	3650 Sq ft			3650		-	$35 per sq ft quoted by Custom Linings 2/1	$ 127,750.00
	Structural Steel Coating (Thickener No. 1 Area)	400 Sq Ft			400		-	$35 per sq ft quoted by Custom Linings 2/1	$ 14,000.00
	Structural Steel Coating (Thickener No. 2 Area)	400 Sq Ft			400		-	$35 per sq ft quoted by Custom Linings 2/1	$ 14,000.00
	Sump Area Grating Replacement	1600 sq ft, 2" thick			1600		-	Grainger grate replace $1,431.70/48 sq ft.	$ 47,723
						0	**0.0**		**$ 624,377**
New Equipment									
	Ferric Sulfate Storage Tank	14' Dia x 12' H, 528 Sq Ft	15,000 gal	SG-3.0	2			Historical CS Quote (2018), plus Epoxy Coating.	$ 63,552
	Ferric Sulfate Day Use Tank	7' Dia x 10' H	2,500 gal	SG-3.0	1			FRP Tank - Historical 2018	$ 17,500
	Potassium Permanganate Bag Breaker				1			Formpak - 2019	$ 18,000
	Polymer Bag Breaker				1			Formpak - 2019	$ 18,000
	ORP Meter (Splitter Box Splitter Box - Section 1)	Hach pH/ORP Sensor		60 °F	1			Hach Published - 2019	$ 456
	ORP Meter (Splitter Box Splitter Box - Section 2)	Hach pH/ORP Sensor		60 °F	1			Hach Published - 2019	$ 456
	Ferric Sulfate Dosing Pump	Grundfos Diaphragm dosing pump	86.5 gph		2	1	0.8	Denver Industrial Pump 3-1-2019	$ 4,842
	Ferric Sulfate Transfer Pumps	Qdos 120 Universal Plus Pump	1.55 gpm	50' TDH, 60 °F	2	2	1.5	233001286 Historical Reference	$ 3,370
	1" Ball Valves				4			Rampart Supply Budgetary Quote 2/19/2019	$ 197
	3" Check Valve				2			Rampart Supply Budgetary Quote 2/19/2019	$ 688.00
	3" Pinch Valve				3			Rampart Supply Budgetary Quote for FLOWROX Valves 3/1/2019	$ 1,876.25
	Lead Chloride Silo and Equipment Assembly		680 ft^3		1	5,5,5	3.8, 3.8,	Historical Silo Quote (2018)	$ 143,500
	Thickener Discharge Lime Agitator	Single Prop, 2.5' Dia, 1800 RPM			2	5	3.8	233001286 Historical Reference	$ 6,500
	Thickener Discharge pH Meter	Hach Analog Differential pH Sensor			2			Ryton Body	$ 1,023
	Sump Area Pump	5 HP, 40 gpm	40 gpm		1	5	3.8	Denver Industrial Pump 3-1-2019	$ 16,094
	Reagent Storage Building	30' x 56'			1			RS Means Factor - Warehouse Mid Range Concrete and earthwork part of factoring	$ 210,000
	Reagent Storage Building Ventilation System				1			233001013 Historical Reference	$ 80,000
	Building Liner	30' x 56'			1			2018 Quote $1/ft2	$ 1,680
						36.0	**27.2**		**$ 672,053**
Project Equipment Total									**$ 8,288,085**

Client: Climax Molybdenum
Project: Climax PDWTP Process Refit
Project #: 233001306
Revision: A

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MECHANICAL EQUIPMENT LIST - Climax Molybdenum - OPTION 10B

Equipment Number	Equipment Name	Approximate Dimensions	Capacity (English)	Design Pressure (atm) and Temp (°C)	Qty.	Unit HP	Operating HP	Vendor Quote/Date	Total Cost ($)
Infrastructure and Safety									
	Reagent Building Safety Shower	2' base	20 gpm		1	0	-	Grainger combination Eyewash and Shower	$ 2,000
									$ 2,000
New Equipment									
	Ferric Sulfate Storage Tank	14' Dia x 12' H, 528 Sq Ft	15,000 gal	SG-3.0	2			Historical CS Quote (2018), plus Epoxy Coating.	$ 63,552
	Ferric Sulfate Day Use Tank	7' Dia x 10' H	2,500 gal	SG-3.0	1			FRP Tank - Historical 2018	$ 17,500
	Potassium Permanganate Bag Breaker				1			Formpak - 2019	$ 18,000
	Polymer Bag Breaker				1			Formpak - 2019	$ 18,000
	ORP Meter (Splitter Box Splitter Box - Section 1)	Hach pH/ORP Sensor		60 °F	1			Hach Published - 2019	$ 456
	ORP Meter (Splitter Box Splitter Box - Section 2)	Hach pH/ORP Sensor		60 °F	1			Hach Published - 2019	$ 456
	Organosulfide Dosing Pump	Qdos 30 Pump	2.92 gal/hr	20' TDH, 60 °F	1	0.33	0.2475		$ 2,495
	Ferric Sulfate Dosing Pump	Grundfos Diaphragm dosing pump	86.5 gph		2	1	0.75	Denver Industrial Pump 3-1-2019	$ -
	Ferric Sulfate Transfer Pumps	Qdos 120 Universal Plus Pump	1.55 gpm	50' TDH, 60 °F	2	2	1.5		$ -
	Lead Chloride Silo and Equipment Assembly		680 ft^3		1	5,5,5	3.8, 3.8, 3.8	Historical Silo Quote (2018)	$ 143,500
	Lead Chloride Transfer Augur		50 ft		1	5	3.75	Assumption	$ 15,000
	1" Ball Valves (New Reagent Building)				4			Rampart Supply Budgetary Quote 2/19/2019	$ 197
	3" Check Valve (New Reagent Building)				2			Rampart Supply Budgetary Quote 2/19/2019	$ 688.00
	3" Pinch Valve (New Reagent Building)				3			Rampart Supply Budgetary Quote for FLOWROX Valves 3/1/2019	$ 1,876.25
	Thickener Discharge pH Meter	Hach Analog Differential pH Sensor			2			Ryton Body	$ 1,023
	Reagent Storage Building	30' x 56'			1			RS Means Factor - Warehouse Mid Range	$ 210,000
	Building Liner	30' x 56'			1			2018 Quote $1/ft2	$ 1,680
					28	**31.33**	**28.50**		**$ 564,030**
Project Equipment Total									**$ 566,030**

APPENDIX E

Option 13 – Build Reduced Flow Molybdenum Treatment Plant and Blend Flows

Appendix E Option 13 – Build Reduced Capacity Molybdenum Treatment Plant and Blend Flows

E.1 REDUCED CAPACITY MOLYBDENUM PLANT

E.1.1 Option Description

In 2011, Climax Molybdenum commissioned a prefeasibility study for the design of a new Molybdenum Water Treatment Plant. Variations of this design have been completed but are all based on building a full-size plant intended to match the design flow for the PDWTP but optimized for molybdenum removal. The full-build out Mo Removal Plant is summarized in **Appendix C** and in the reports prepared for this design.

As a potential alternative, a reduced capacity molybdenum treatment plant is conceived that would take a split-stream portion of the flow from the metals removal portion of the PDWTP. The portion of flow treated for molybdenum removal would be blended with the untreated portion of the split-stream prior to discharge at Outfall 002A. A high-level approach to cost estimating for this option is presented by applying a factoring approach to the current full build out plant design, currently projected to Cost $79,652,000 (CAPEX + OPEX).

As described in the main narrative, Option 13 would work in conjunction with the current PDWTP and would optimize the treatment of Mo at flow rates between 25 and 50 percent of current design flow for the existing PDWTP.

E.1.2 Capital Expenditure

Based on the recent scoping of the full-scale plant depicted in Option 9, the updated cost estimate from quotations in July 2017, escalated to 2019 numbers, is $79,652,000. Using current cost estimating methods based the six-tenths scaling factor, the estimated costs for reduced capacity Mo Removal Plants are provided in **Table E-1**.

Table E-1. Option 13 Capital Cost Estimate Summary

Description	**Option 9**	**Option 13**	
	100% Capacity	**50% Capacity**	**25% Capacity**
Labor	12,111,000	$7,990,280	$5,271,619
Material	13,868,000	$9,149,468	$6,036,398
Subcontractor	13,562,000	$8,947,583	$5,903,203
Equipment	3,018,000	$1,991,137	$1,313,661
Sub-total	**42,559,000**	**$28,078,468**	**$18,524,881**
Material Sales & Use Tax	970,000	$639,961	$422,217
Construction Equipment Tax	212,000	$139,868	$92,278
Sub-total	**1,182,000**	**$779,829**	**$514,495**
Owner Furnished (O.F.) Items	11,955,000	$7,887,359	$5,203,716
Tax on O.F. Items	836,000	$551,554	$363,890
Sub-total	**12,791,000**	**$8,438,913**	**$5,567,606**
Contingency	8,463,000	$5,583,498	$3,683,735
Sub-total	**8,463,000**	**$5,583,498**	**$3,683,735**
Construction Management	3,669,000	$2,420,637	$1,597,025
Engineering/SDCs/Commission	5,534,000	$3,651,078	$2,408,813
Sub-total	**9,203,000**	**$6,017,715**	**$4,005,838**
Owner's Costs	5,454,000	$3,598,298	$2,373,991
Total	**$79,652,000**	**$52,550,721**	**$34,670,546**

E.1.3 Operation Costs

Operating costs prepared by Golder (2017) for a full-scale Molybdenum Removal Plant, as outlined in Option 9, are used to scale the operating costs for a reduced capacity blending approach. Most cost reductions are considered linear except for individual rate items that do not follow normal scaling including laboratory testing and maintenance. Laboratory testing is not scaled as it would be based on the frequency of sampling rather than flow rates.

Table E-2. Option 13 Operation Cost Estimate Summary

Mo Removal Plant - Operation Cost Estimate			
Item	**Full Scale Cost**	**50% Scale**	**25% Scale**
Facility General Maintenance	$836,000	$551,554	$363,890
Chemical	$1,339,000	$669,500	$334,750
Electrical	$181,000	$90,500	$45,250
Operations Staff	$411,000	$205,500	$102,750
Sludge Hauling	$47,000	$23,500	$11,750
Laboratory Analysis	$15,000	$15,000	$15,000
Total	**$2,829,000**	**$1,555,554**	**$870,390**

APPENDIX F

Option 14 – Removal of Molybdenum from Tailing Stream

Appendix F Option 14 – Removal of Molybdenum from Tailing Stream

F.1 TAILINGS TREATMENT PROCESS

F.1.1 Option Description

The purpose of Option 14 is to provide direct treatment of soluble molybdenum in the tailings disposal line (TDL) prior to discharge into the Mayflower TSF. This option specifically targets soluble molybdenum associated with the processing of oxidized ore. Implementation of Option 14 does not require modifications to the existing water treatment facilities or the mill. Ferric iron additions would occur in HDPE sections of the TDL, which are located above the Mayflower TSF. Lime would be added at the same location to provide pH control for optimum Mo removal conditions. Three locations were identified as points of reagent addition that could be used: (1) the Clinton Cutout disposal point into the Mayflower Pond, (2) the East Cutout, and (3) the No. 22 Drop Box near the crest of 5 Dam.

The following describes the cost basis of a strategy for implementing Option 14. The proposed changes are primarily intended for treatment of soluble molybdenum (Mo) associated with oxidized ore. This option focuses on placement of a ferric sulfate tank battery and a hydrated lime storage and slurry system adjacent to the TDL discharge into the Mayflower Pond. Two primary locations have been identified: near the East Cutout and the No. 22 Dropbox. A supplemental third point, as necessary, has been identified in the Mayflower pond when the Clinton Cutout is depositing. Addition of ferric sulfate to the tailing slurry from the mill will cause coprecipitation of soluble Mo in the TDL during transport and discharge to Mayflower TSF. To counteract the acidification of the tailings (from ferric iron precipitation), lime slurry will be added to the line to maintain a pH near 4.5. Lime addition is expected to increase the pH of the tailings from less than 3 (based on a 30 mg/L Mo concentration) to the target range from 4.5 to 5. The hydrated lime addition will be from a new storage, makeup, and feed system located near the East Cutout from the TDL. Makeup water for the lime slurry process will be provided from the PDWTP effluent. The two identified TDL injection points are chosen based on proximity to a final discharge line constructed of HDPE, which is compatible with the low pH conditions. If the tailings discharge is diverted upstream at the Clinton Cutout, lime and ferric iron will be piped to the location where the Clinton Cutout deposits into the Mayflower TSF.

The concept is that the molybdenum removed by adsorption to ferric oxyhydroxide during transport of tailing slurry would be sequestered within the tailing upon discharge to the TSF. The slurry water, with soluble molybdenum substantially removed, would migrate to the decant pond where the barge pumps would transfer the water either back into the mill circuit (via Robinson Lake) or to the PDTWP for treatment and discharge from the site.

The pH of the Mayflower decant system water would need to be neutralized in order to protect the barge pump system and related piping infrastructure. Neutralization would occur via what has been conceptualized as a lime dosing header. Stantec assumed that this method of neutralization would be effective and that would not require modification to the barge pumps or downstream facilities. Implementation of the decant system water neutralization is not included in the Option 14 cost estimates because this process is likely required in the future when 3 Dam and 5 Dam seep water contributions are expected to influence conditions in the Mayflower TSF.

F.1.2 Capital Expenditure

Installation of a ferric sulfate tank battery on the bench near the Mayflower Pond between the East Cutout and the No. 22 Dropbox would be the main distribution location for the ferric sulfate reagent. The tanks would be epoxy-lined, carbon steel and would be wrapped with heat tape and 2 inches of insulation for winterization. Composite stairs and platforms on coated steel structural supports would be used to access the tanks for maintenance and inspection. Two ferric sulfate metering pumps would be located under the shared platform. Each pump discharging into a shared header.

The lime slurry system would be comprised of a dry storage of 50 tons of hydrated lime and a mixing tank. An HDPE trenched line of treated PDWTP water will be routed to the lime slurry tank for daily reagent makeup. The 500-gallon lime slurry tank will be wrapped with heat tape and 2 inches of insulation. Electrical accommodations between the two reagent systems will be shared. Lime slurry will be constantly circulated to keep the line from drying out or solidifying.

Stantec assumed that the tanks will be placed near the East Cutout above the feed into Mayflower Pond. Pumps will be configured to feed to any of the locations using a local valving arrangement. The pipeline route to the East Cutout measures roughly 200 feet and requires crossing the adjacent road. The pipeline to the No. 22 Dropbox is routed along the road and toward the existing tank battery. The Clinton Cutout supplemental pipeline is roughly 1,900 feet from the chemical tank battery and follows the topographic contours to the point of application. Electrical distribution would require a drop to a new transformer and installation of associated panels.

Required surface coatings, pumps, and valving have all been quoted by local vendors. For equipment of the same size as equipment quoted in the past year, historical information is used. Concrete and earthwork are estimates based on local ground work requirements only at recent contractor rates from 2018. Equipment installation, project ancillaries, and piping costs are factored according to industry standard methods.

All indirect costs related to Option 14 are estimated within industry standard ranges for factors applied. Engineering and construction management costs are at the lower end of the industry range. Industry freight, equipment rental, consumables, startup, mobilization, and project insurances are quoted at the mid-range given the size of the project.

As noted previously, these costs do not consider any protection for barge pumps or infrastructure associated with the Mayflower TSF.

The expected capital expenditure of Option 14 is $7,022,000 USD. The summary of the cost makeup is included in **Table F-1**.

This cost is presented with 6.99% taxes on Materials and Rentals, a 40% contingency, and an 8.8% Owner’s cost. Construction Management costs are estimated at 12%. Engineering Costs are presented as a 12% factor of capital (based on the large project size), and a flat rate of $200,000.

Table F-1. Option 14 Capital Cost Estimate Summary

Tailings Coprecipitation Process - Capital Cost Estimate

Cost Item	Cost Factor	Cost
Labor		$660,491
Materials		$537,965
Subcontractor		$872,000
Equipment		$1,627,985
Subtotal		**$3,698,442**
Material Sales and Use Tax	6.99%	$37,604
Construction Equipment Tax	6.99%	$113,796
Subtotal		**$151,400**
Contingency	40%	$1,539,937
Subtotal		**$1,539,937**
Construction Management	12%	$432,000
Engineering/SDCs/Commission		$632,000
Subtotal		**$1,064,000**
Owners Cost	8.8%	$567,932
Total		**$7,021,711**

F.1.3 Operation Costs

The tailing slurry co-precipitation approach adds ferric sulfate at two locations of the TDL just downstream of the East Cutout and to the final discharge at the 5 Dam crest at the No. 22 Drop Box. When tailings are diverted at the Clinton Creek Cutout, reagents can also be fed to the Clinton Creek deposition point in the Mayflower pond. Makeup water for lime slurry is supplied from a pipeline routed from the PDWTP. The ferric sulfate tank will be heat traced and insulated for winter operations. Power for pumping of both reagents is assumed to use existing power and will only require power cabling. Lime addition to the tailing line will occur by one of two pumps using the lime slurry from the new lime slurry makeup tank.

All new reagents were quoted by vendors for this project at FOB costs. Lime costs and shipping is based on historical quotes received.

Electricity is estimated for the new equipment after power factor considerations at $0.15/kWh.

The lining of the ferric sulfate tanks for this option includes quarterly inspection. Cost for the quarterly inspection is currently estimated assuming each inspection would be completed by two, third-party liner inspection technicians over a two-day period, four times per year.

The annual estimated operating costs for Option 14 is $6,269,000 USD, and includes reagents, electrical power, and inspections. The mill is assumed to be discharging 75% of the year and is incorporated into the annual cost column. Usage rates and itemized costs are included **Table F-2**.

Table F-2 Option 14 Operating Cost Estimate Summary

Ferrihydrite Process - Operating Cost						
Reagent Costs						
ITEM	**Usage lb/day**	**Weekly Usage**	**Cost US$/lb**	**Delivery to Site**	**Cost to Site**	**2019 Cost (75% Availability)**
Hydrated Lime (89%)	10,286	72,002	$0.20	$0.04	$0.24	$757,235
Ferric Sulfate (58%)	32,880	129,535	$0.58	$0.02	$0.60	$5,415,665
Total Reagent Costs						**$6,172,899**
Energy Costs						
ITEM				**$/kWh**	**Total kW**	**2019 Cost**
Electricity				0.15	71	$70,364
Maintenance						
ITEM	**Qty**	**Days**	**Daily Rate**	**Frequency**	**Trip Cost**	**2019 Cost**
Liner Inspection	2	2	1500	4.00	250	$26,000
Total Annual Cost						**$ 6,269,263**

F.1.4 Option 14 Supporting Documentation

The ferric sulfate tank battery consists of three 14-foot diameter tanks, each 12-feet tall with appropriate insulation jacketing. The platform access to the top of the three tanks is a standard 3-foot wide platform to access the level transmitters and scrubbers on top of the tanks. This arrangement is shown in **Figure F-1**.

Lime preparation equipment is based on an existing design that is in the field and operating at a Stantec supported facility. The Lime system includes a 50-ton silo, feed pumps, a 500-gallon slurry tank, and a local system to maintain the slurry.

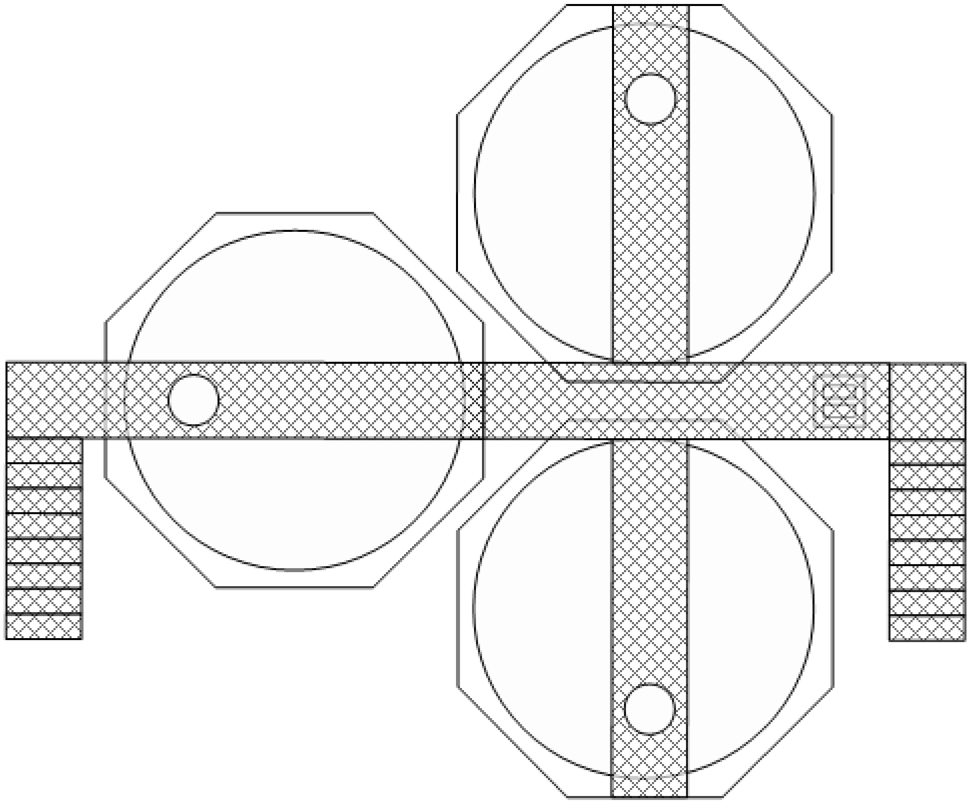

Figure F-1. Option 14 Ferric Sulfate Tank Battery

An equipment summary has been developed on the discussed basis previously. Measurements for the equipment list were based on satellite images from Google Earth along the roads on site. See the attached equipment list for a summary of preliminary sizing and infrastructure requirements for this option.

Infrastructure changes discussed for Option 14 are outlined in Figure 1 attached. The Proposed bench for the tank battery and the pipeline routes are depicted in green with tie in points to existing infrastructure labeled per the description.

Client: Climax Molybdenum
Project: Climax PDWTP Process Refit
Project #: 233001306
Revision: B

MECHANICAL EQUIPMENT LIST - Climax Molybdenum - Option 14

Equipment Number	Equipment Name	Approximate Dimensions	Capacity (English)	Design Pressure (atm) and Temp (°C)	Qty.	Unit HP	Operating HP	Vendor Quote/Date	Total Cost ($)
					0	**0**	**0.0**		
New Equipment									
	Ferric Sulfate Tanks	14' Dia x 12' H, 528 Sq Ft	15,000 gal	SG-3.0	3			Historical CS Quote (2018), plus Epoxy Coating.	$ 190,656
	Ferric Sulfate Metering Pumps		0-86.5 gph	140 psi, ambient	2	1	0.75	Denver Industrial Pump 3-1-2019	$ 9,684
	Lime Slurry System, Sodimate	12' Dia x 50' Total H	3,098 ft^3	50 ton capacity	1			Historical Quote 2018, 233001286, Contractor Quote	$ 394,000
	Includes silo, dust collection, vent shaker, level detection, slide gates, activator, feeder, lime slurry tank, control panel.				1	5.75	4.3125	4 Motors at 0.75 HP, 1.5 HP, 2.0 HP, and 1.5 HP	*SEE ABOVE* *SEE ABOVE*
	Milk of Lime Metering Pumps		15 gpm	60 psi, ambient	2	2	1.5		$ 3,880
	PDWTP Effluent Water Pumps		30 gpm	400 ft, ambient	2	20	15	Historical Quote 2018, 233001286, Contractor Quote	$ 78,000
	Self Contained Safety Shower (Ferric Suflate Tank Area)	2' base	20 gpm	ambient	1	5	3.75	HAWS	$ 12,000
	Deck Grating	5 - 3' x 12 ft sections, Per tank			5		-	Grainger grate $1,431.70 / 16' Linear Section.	$ 7,155
	Deck Grating Replacement Stairs	12 feet			2		-	Grainger grate $1,431.70 / 16' Linear Section.	$ 2,862
	Concrete Lining Pads	242 Sq ft.			3		-	35$ per sq ft Custom Lining	$ 25,410.00
	Tank Insulation Tracing	1984 Sq Ft. per tank			1		-	10$ per sq ft - Banks Industrial Group	$ 59,520.00
	Tank Heat Tracing (Ferric Sulfate Tanks)	Per Tank: 15 zones, 44 linear ft each, 10W/ft			1980	35.4	26.55	$15.75/ft Heating Elements Plus, 2 Thermostats and Distribution Panels (load limited) [per tank]	$ 33,747
	Tank Heat Tracing (Lime Slurry Tank)	Single tank: 4 Zones, 50 ft each, 10W/ft			201	3.6	2.70	$15.75/ft Heating Elements Plus, 1 Thermostat, distribution panel shared with Above Entry	$ 7,757
	Structural Steel Coating (Ferric Sulfate Tank Area)	8 posts, 15 ft tall each, cross bracing			82		-	35$ per sq ft Custom Lining	$ 4,305.00
	HDPE Piping (2") (Makeup water)	12,600 ft from SDP to 5 Dam Crest			12600			$20/ft buried and trenched pipe	$ 252,000.00
	HDPE Piping (2") [Ferric Sulfate]	5500 ft			6230			$20/ft buried and trenched pipe	$ 124,600.00
	Carbon Steel pipe 2" [Lime Slurry]	5500 ft			6230			$12/ft buried and trenched pipe	$ 74,760.00
	Level Transmitter	Radar		Ambient	4		-	Assumed	$ 20,000
	Power Distribution Cable	1000 ft required			1000			$1.65/ft (1 AWG) Graybar, 10$/ft trenching	$ 11,650
	250 KVA Transformer				1			250 kVA Schneider Electric	$ 43,535
							-		
						95.7	**71.8**		**$ 1,311,985**
Project Equipment Total									**$ 1,311,985**

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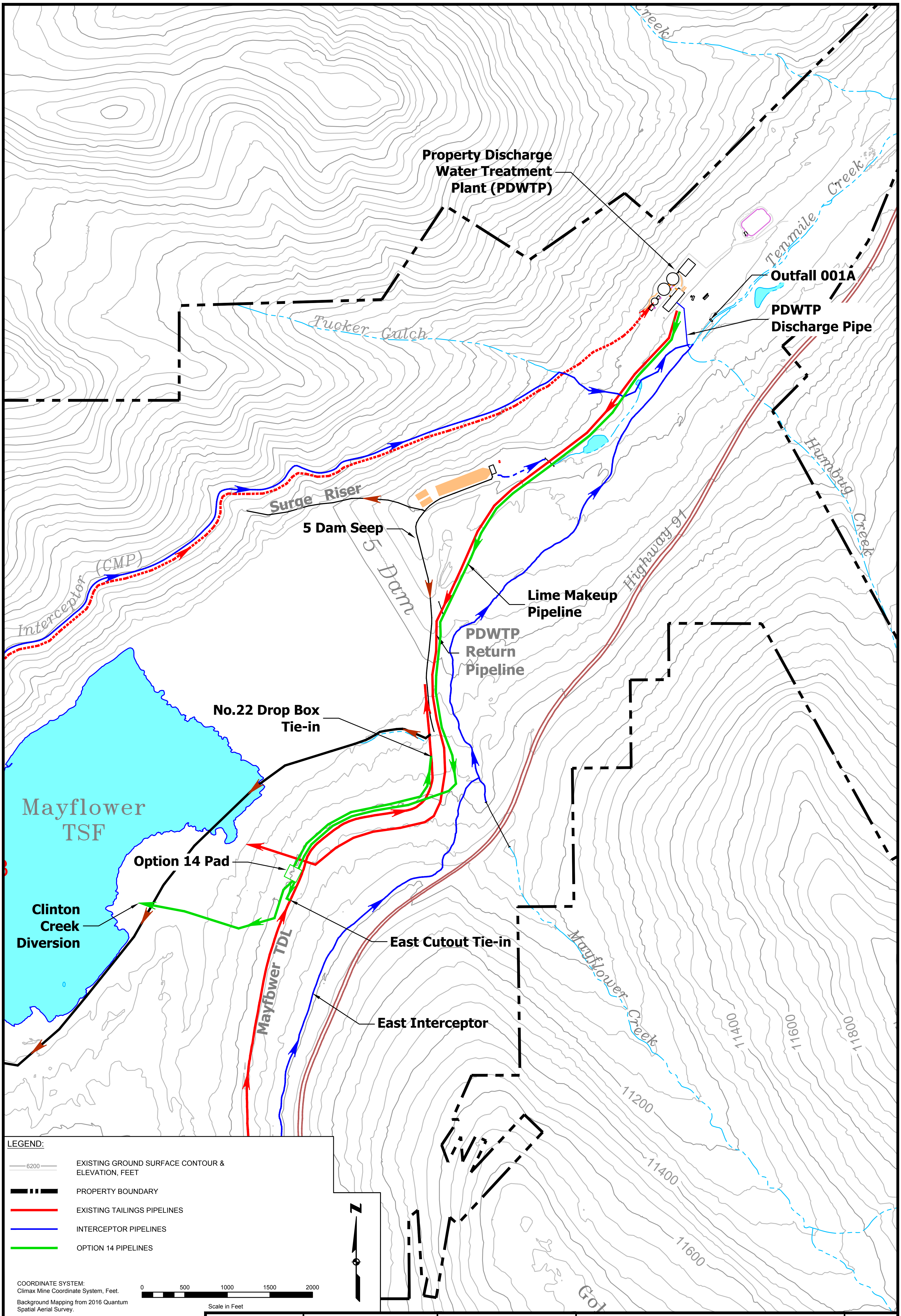

DESIGNED K REED
CHECKED D GRILLS
APPROVED D DUPON

Stantec

Climax Molybdenum
A Freeport-McMoRan Company

CLIMAX MINE

FIGURE 1
OPTION 14 SITE LAYOUT

FIGURE
1
APR 2019