6. GEOCHEMISTRY

6.1 INTRODUCTION

Metal leaching and acid rock drainage potential is linked to the geochemical characteristics of geological materials proposed to be disturbed by the Harper Creek Project (the Project). Acid rock drainage (ARD) refers specifically to leaching of these materials under acidic (low pH) conditions arising from sulphide mineral oxidation in the absence of acid neutralizing minerals, whereas metal leaching (ML) refers more generally to leaching regardless of pH (i.e., including pH neutral and non-acidic conditions).

This chapter presents the baseline geochemical conditions, and development of geochemical sources terms used to:

- assess Project effects on water quality as a result of the Project; and
- develop the Mine Waste and ML/ARD Management Plan (Section 24.9).

This chapter is a summary of a detailed report prepared by SRK Consulting (Canada) Inc., which is presented in Appendix 6-A. Use of the source terms for water quality predictions are described in Chapter 13, Surface Water Quality Effects Assessment.

6.1.1 Valued Component Scoping

A preliminary list of proposed valued components (VCs) was drafted early in project planning based on the expected physical works and activities of the reviewable project; type of project being proposed; local area and regions where the proposed project would be located; and consultation with federal, provincial, and local government agencies. ML/ARD was excluded as a VC for the reasons described below.

ML/ARD has the potential to affect surface water and groundwater quality during the Construction, Operations, and Closure phases. As a result, while geochemical processes themselves are not considered a VC, effective ML/ARD characterization, prediction, and management of excavated and exposed geological materials are critical in preventing deleterious effects to the receiving environment, i.e., surface water and groundwater VCs. Geochemistry studies and analyses are presented in the ML/ARD Characterization Report (Appendix 6-A) and will be used to support the effects assessment of relevant receptor VCs. A Mine Waste and ML/ARD Management Plan is also included in Section 24.9.

6.1.2 Consultation Feedback

A summary of how consultation feedback was incorporated into the assessment subject areas is summarized below in Table 6.1-1.

Table 6.1-1. Consultation Feedback

Subject Area	Feedback by*			Issues Raised	Response
	AG	G	P/S		
ARD	X	X	X	Acidic drainage	The potential for acidic drainage was characterized and assessed.
Neutral ML	X	X	X	Effect of metal leaching under neutral pH conditions	Geochemical source terms were incorporated into the water quality model that considered metal leaching under all pH conditions.
Dam construction	X	X		Tailings management facility's effect on downstream environment	Geochemical source terms were incorporated into the water quality model to assess downstream effects.
Storage of PAG material	X		X	Acid generation from rocks in the tailings area	ML/ARD characterization and geochemical source term development considered material in the tailings area.
Upper bound case		X		More realistic upper bound case than the 95th percentile case developed for the EA	A modified upper bound case, "Realistic Upper Limit" has been developed and replaces the upper bound case presented earlier

**AG = Aboriginal Group; G = Government; P/S = Public/Stakeholder.*

6.2 Regulatory and Policy Framework

The following regulatory guidance documents were referenced to develop the ML/ARD characterization plan.

- *Policy for Metal Leaching and Acid Rock Drainage at Minesites in British Columbia* (BC MEM 1998a).
- *Guidelines for Metal Leaching and Acid Rock Drainage at Minesites in British Columbia* (BC MEM 1998b).
- *Water and Air Baseline Monitoring Guidance Document for Mine Proponents and Operators* (BC MOE 2012).
- *Prediction Manual for Drainage Chemistry from Sulphidic Materials* (Price 2009).

6.3 Baseline Conditions

6.3.1 Regional and Historical Setting

6.3.1.1 Geological Setting

The Project Site is located within structurally complex low-grade metamorphic rocks of the Eagle Bay Assemblage, which is part of the Kootenay Terrane on the western margin of the Omineca Belt. This assemblage hosts numerous small polymetallic massive sulphide deposits found mainly within in Devonian age felsic volcanic rocks. These deposits formed in an arc volcanic environment in response to eastward subduction of a paleo-Pacific ocean.

The host rocks of the mineralization at Harper Creek are a succession consisting of orthogneiss, metasediments, metavolcanics and metavolcanic clastics. The dominant rock types are schists and phyllites with variable quartz content. Ten distinctive large-scale lithological packages that correlate between drill holes have been defined that show property scale layering with a northerly dip. Pyrite and pyrrhotite occur throughout the sequence as fine disseminated grains and porphyroblasts. Other sulphide minerals occurring at trace levels include sphalerite, galena, arsenopyrite, tetrahedrite-tennanite and cubanite.

Some lithological packages are noted to be calcareous. Carbonate minerals include calcite, dolomite and iron-carbonates. The presence of iron carbonates is apparent by the abundant characteristic staining of old core by weathering.

Appendices 5-A and 5-H provide more details on geological setting.

6.3.1.2 Mineral Deposit Classification

The classification of mineral deposits is important because it allows a subject property to be compared with other sites and possibly provides a source of analogous geochemical data which may be used to predict the performance of the site under study.

Merit Consultants International Inc. (Merit 2014) indicated that:

> *Harper Creek is interpreted to be a polymetallic volcanogenic sulphide deposit, comprising lenses of disseminated, fracture-filling and banded iron and copper sulphides with accessory magnetite. Mineralization is generally conformable with the host-rock stratigraphy, as it is consistent with the volcanogenic model. Sulphide lenses are observed to measure many tens of metres in thickness with km-scale strike and dip extents.*

The Harper Creek deposit is thought to be a re-mobilized volcanogenic massive sulphide deposit (Merit 2014) and it is classified as kuroko-type in the BC Mineral Inventory File (BC MEM 2011). However, it has very little massive sulphide mineralization with the exception of 5-metre (m)-thick lenses in Package D. Harper Creek lacks the different types of distinctive sulphide mineralization often observed in some types of massive sulphide deposits including the presence of barite, sphalerite, and galena. Other Kuroko-type deposits in British Columbia include the nearby Samatosum Deposit, Britannia, Myra Falls, and Eskay Creek. These deposits are all characterized by more complex massive sulphide mineralization than observed at Harper Creek.

It is concluded that there are no direct analogs for the Harper Creek deposit; however, volcanogenic deposits are considered the nearest similar deposit type.

6.3.1.3 Previous Geochemical Studies

No previous work on ML/ARD characterization has been published.

6.3.2 Baseline Studies

6.3.2.1 Design of Studies

The following are the two objectives of the geochemical testing program and interpretations:

- Provide design criteria for the operation and management of the various facilities containing geological materials at the Project Site to the Project engineers. These criteria can include segregation criteria to address ARD potential, criteria to define exposure times for reaction materials, and recommendations for construction of facilities such as placement methods.
- Predict the chemistry of water coming into contact with geological materials as "source terms" for inputs into water quality models for the Project Site.

The geochemical characterization program was developed by listing all possible facilities for the mine, then defining a conceptual geochemical model for each facility. These in turn were used to define data needs.

Twenty-five different mine component/facilities that could be sources of chemical loads and other parameters to surface and groundwater were identified during development of the mine plan for the Project Site. Variants within the sources (for example, sub-aerial, flushing, and submerged for PAG rock) resulted in 34 individual source terms for input into the overall site water quality model.

6.3.2.2 Methods

Sample Acquisition

Samples of waste rock, ore, overburden, quarry rock, and simulated tailings were acquired for testing as follows:

- waste rock and ore samples were obtained from drill core used to define the geological setting and economic value of the mineral deposit;;
- simulated tailings samples were prepared during metallurgical testwork;
- overburden samples were obtained by drilling and testing programs in the footprint of the open pit and facilities where overburden stripping will occur; and
- quarry rock samples were obtained from geotechnical drilling in the vicinity of a borrow source for tailings dam construction.

Appendices 5-H and 6-A provide more details on geological setting, sample location and acquisition.

Geochemical Testing

Geochemical testing methods used for the ML/ARD characterization included:

- static geochemical testing:
  - sulphur forms (total and sulphate);

  - neutralization potential determined by Modified Acid Base Accounting (Coastech 1991) method;
  - total inorganic carbon determined by coulometric methods;
  - paste pH determined by Sobek et al. (1978);
  - paste conductivity using the same procedure as the paste pH;
  - element scan (including sulphur) using inductively coupled plasma following a 4-acid digestion, including low level Hg;
- mineralogy:
  - optical mineralogy;
  - Rietveld x-ray diffraction;
  - electron microprobe on mineral grains;
  - Quantitative Evaluation of Minerals by Scanning Electron Microscopy (QUEMSCAN®);
- leach tests:
  - Shake flask extraction method of Price (2009) was used for smaller samples;
  - Meteoric water mobility procedure (Nevada Division of Environmental Protection 1997) for larger samples;
- humidity cells using the method of Price (2009). All tests were operated for a minimum of 40 weeks while some tests have continued for more than 2.5 years;
- on-site kinetic tests ("barrels"). These tests were monitored for two complete field seasons in 2012 and 2013. These tests were performing using test protocols developed for previous projects with modifications for this Project;
- unsaturated columns. These tests were performed using a Project-specific methodology primarily to simulate site conditions;
- saturated columns. These tests were performed using a Project-specific methodology; and
- stored bag tests. These are a new protocol developed for the Project to evaluate accumulation of weathering products in oxidizing material not subject to leaching.

Appendix 6-A, ML/ARD Characterization Report, provides more details on these programs.

6.3.2.3 *Limitations*

All methods used for the Project have been previously used on other projects in the same form or with some minor modifications. The primary limitation with the procedures is that in most cases the results have to be interpreted for application to full-scale conditions. This limitation was addressed in two ways. Firstly, parallel laboratory and on-site tests were performed on the same materials. Secondly, assumptions used to interpret laboratory testwork were designed to ensure outcomes were more likely to over-estimate rather than under-estimate Project effects. These assumptions were also tested using sensitivity analyses.

6.3.3 Existing Conditions

6.3.3.1 Waste Rock and Ore Characteristics

ARD Potential

ARD potential for waste rock at the Project was evaluated using total sulphur to measure acid potential and a site-specific calculation of neutralization potential (NP*) which accounted for the effects of iron carbonates and silicates. It was also determined that calcium concentrations determined by acid digestion could be used to estimate neutralization potential, allowing the large exploration database containing sulphur and calcium analyses to be used to evaluate ARD potential.

Waste rock ARD potential at the Project Site was determined to vary from potentially acid generating (PAG, as defined by NP*/AP ≤ 2) to non-PAG. Sulphur concentrations varied from less than 1% to up to 3%. NP* varied from less than 10 to greater than 100 kilograms (kg) $CaCO_3$/tonne (t). NP*/AP decreased as sulphide content increased. Both rock types and lithological package may be controlling variables for ARD potential but variations in NP*/AP cannot be conclusively linked to specific rock types or packages.

Downhole variation in NP*/AP was examined to evaluate the feasibility of waste segregation based on ARD potential. It was determined that PAG rock occurs in large blocks but that non-PAG rock occurs at smaller scales that will require delineation at the blast scale to ensure that non-PAG rock does not contain mixed in PAG rock. However, even if PAG rock proportions in segregated non-PAG exceed 10%, the mixed rock will remain classified as non-PAG.

Observations from the Project Site and kinetic tests showed that acidic conditions are very slow to develop. In particular, naturally weathered mineralized rock overlying the mineral deposit and old drill core in boxes showed weak development of acidity despite what is decades to more than centuries of exposure to weathering.

Metal Leaching Potential

Evaluation of whole rock concentrations showed that relative to global average concentrations for comparable rock types, rock at the Project Site is primarily enriched with respect to copper, selenium and zinc. These elements are associated with sulphide minerals, and therefore higher ML potential can be expected to be correlated with rock with higher ARD potential, and in the case of copper selenium, correlation with ore can also be expected.

Pit Walls

Pit wall exposures will have the same characteristics as waste rock and will include both PAG and non-PAG components.

6.3.3.2 Tailings

Samples of rougher tailings contained 0.8 to 1% sulphur and were classified as non-PAG based on NP/AP exceeding 2. Cleaner tailings had NP/AP less than 1 and were classified as PAG.

6.3.3.3 Overburden

Overburden from outside the footprint of the open pit had low ARD potential due to APs typically less than 10 kg $CaCO_3$/t. APs were higher for pit overburden reflecting the presence of mineralized rock and sulphur concentrations exceeding 1%. Three samples were classified as PAG due to NP/AP < 1.

6.3.3.4 Quarry Rock

Chemical analysis indicated granitic quarry samples had low sulphur levels, ranging between 0.03 and 0.04%. ARD potential of quarry is considered negligible. Chromium concentrations were found to be enriched using the same methodology as described in Section 6.3.3.1 though chromium is not expected to be in a mineralogical form that allows it to be mobilized.

6.4 DEVELOPMENT OF SOURCE TERMS

6.4.1 Introduction

"Source terms" refers to predicted concentrations for waters in contact with various types of geologically-sourced material and surfaces under the expected disposal conditions at the Project Site. For example, the source term for a waste rock storage area is the concentration found in pore waters within the facilities. These source term predictions become inputs (or terms) to the overall site-wide water and load balance model used to assess potential effects of the Project on the receiving environment. This model has been developed by Knight Piésold and is presented in Chapter 13, Surface Water Quality Effects Assessment.

Source terms are calculated based on information acquired from various sources, including results of laboratory testing and data from other sites. As such, the calculations contain uncertainty which needs to be reflected in the subsequent affects assessment for the Project. The approach used for the Project reflects typical practice in British Columbia by modelling to reflect two conditions or cases. The overall intent of source term predictions is to err on the side of conservatism. The first case uses typical inputs to the source term calculation that is intended to indicate the expected outcome of the proposed waste and water management approach. This is referred to as the "expected case." A second case ("upper bound case") considers upper limit uncertainty in the inputs that are intended to bound calculated concentrations in the source terms. The approach of providing two deterministic cases that represent typical and extreme conditions has been adopted rather than a truly probabilistic approach because there is generally not a strong basis on which to define the probability distributions of inputs into the source term calculations.

The upper bound case presented in the EA represents an extreme condition that is considered to have a very low but unquantified probability of occurring. As a result, a second "modified" upper bound case ("Realistic Upper Limit") has been developed to provide a more realistic probable upper limit outcome to which a probability can be assigned. The details of this Realistic Upper Limit case are provided in Appendix 6-A of the Application /EIA..

Source terms were calculated as average annual, and dissolved in water for each year of the Project using waste quantities and estimates of infiltration developed by others. Seasonal variations were not considered though experience indicates that source concentrations may decrease during high flow events such as spring snowmelt.

Results from using the source terms to evaluate Project effects are described in Chapter 13, Surface Water Quality Effects Assessment (Expected and Upper Bound Cases) and Appendix 13-E (Realistic Upper Limit).

6.4.2 Source Term Methods

Source terms were calculated on the basis of the conceptual geochemical models for each source used to design the characterization program. These can be grouped into sub-aerial sources, flushed sources (i.e., as a result of inundation during flooding), and submerged sources. Additional explanation of the calculation of each source term is provided below.

6.4.2.1 Sub-aerial Facility Terms

The dominant sub-aerial facilities are the permanent non-PAG waste rock dumps, temporary low-grade ore stockpiles, the exposed components of the PAG waste rock dumps before they are submerged, and rougher tailings adjacent to the tailings dams. Minor facilities included infrastructure constructed from waste rock, overburden and soil stockpiles, rock fill constructed from quarry rock, and pit walls.

The method used for sub-aerial sources was to estimate weathering rates using laboratory kinetics, adjust weathering rates for site conditions, dissolve load released by weathering using expected infiltration to obtain the dissolved contact water concentration, and finally to adjust the contact water concentration to reflect solubility of weathering products.

Two aspects of the calculation particularly consider uncertainty. Firstly, the weathering rates used as inputs were based on the 50th and 95th percentile rates indicated by humidity cells and represent the expected and upper bound cases. Secondly, the solubility of weathering products varies. For the majority of dissolved ions, pH is the main controlling variable with concentrations possibly varying over several orders of magnitude for one pH unit depending on the charge on the ion and the pH.

Data on the variation of solubility as a function of pH was largely derived from a dataset of waste rock seepage chemistry for geologically analogous mine sites. The use of existing data from mine sites provides the greatest confidence that concentrations used to develop the source terms are likely to be realized. As noted in Section 6.3.1.2, Harper Creek is interpreted to be a “remobilized volcanogenic massive sulphide deposit” closest to Kuroko-type. Seven analogous mines with public domain drainage water chemistry data were identified and assembled into a database. Statistical summaries were prepared on the basis of pH measurements. The expected case was based on 95th percentile concentrations of drainage with pH greater than or equal to 8. The upper bound case was based on the 95th percentile concentrations of drainage with pH between 7.6 and 8. Lower pHs are considered for the Upper Bound Case to reflect the natural variation in pH indicated by sites with analogous waste rock characteristics including the presence of PAG rock that has not become acidic which is expected to be the case for Harper Creek. Confidence that the expected case is reasonable was demonstrated by the similarity of the full-scale Kuroko-type analog data with water chemistry obtained from on-site kinetic tests and laboratory column tests.

Sulphate concentrations were constrained in the calculations using the modelling of the so lubility of gypsum for the expected major ion chemistry of drainage. Selenium solubility was assumed to be linked to sulphate concentrations and gypsum solubility.

The factor used to scale humidity cell rates to site conditions were not varied for the two cases because the range over which these could vary was observed to be much narrower than solubility limits. Weathering rate comparisons for humidity cells and on-site kinetic tests showed that rates were lower under field conditions and the difference in rates could reasonably be assigned to temperature and particle size differences.

6.4.2.2 Flushing Terms

Flushing terms provide the specific load released from weathered rock that has not been flushed at its storage location by infiltrating water. These terms include load released from stockpiled low-grade ore during processing, run of mine ore, and PAG rock as it is flooded in the tailings pond.

The calculation method is based on the rate of weathering (expressed as milligram (mg)/kg/week) indicated by kinetic testwork multiplied by the duration of exposure of the rock prior to flushing. For the expected case, the rate of weathering was reduced to account for the effect that frequent (weekly) thorough leaching in humidity cells appears to accelerate weathering compared to less frequent leaching as will occur off flow paths in full-scale facilities. The upper bound case did not adjust for this effect. A Project-specific procedure has been developed and implemented to evaluate this effect. Results will be available early in the EA review stage.

6.4.2.3 Submerged Sources

Submerged sources include PAG waste rock following submergence, saturated rougher tailings below the water table in the tailings impoundment, and cleaner tailings. Submergence is a proven technology to limit weathering due to sulphide oxidation.

Leaching from subaqueous wastes is primarily a function of the solubility of primary minerals in water. The majority of minerals hosting important trace elements (including sulphides) are highly insoluble in water. Carbonates are the most soluble minerals but these are expected to dissolve slowly as pore water chemistry comes to equilibrium with them.

For materials disposed in the tailings impoundment, pore water chemistry will be determined by the composition of process water during operation and in to closure. In the future, the process water will be displaced and pore water chemistry will reflect the interaction of water with minerals in the wastes. This future water chemistry was estimated using sub-aqueous column tests.

6.4.2.4 Nitrate Leaching

Nitrate leaching due to explosives use was calculated using the Ferguson and Leask (1988) method.

6.5 ML/ARD Management Plan

The ML/ARD Management Plan is an outcome of the ML/ARD potential characterization. The plan itself is provided in Section 24.9. Essential components of the plan are described below:

- waste rock, pit area overburden, and low-grade ore will be segregated according to ARD potential in the open pit for separate disposal;
- non-PAG waste rock and overburden will be placed in permanent stockpiles and closed in place;
- PAG waste rock will be placed in the tailings impoundment so that it becomes submerged within two years;
- all low-grade ore is scheduled to be processed prior to closure in Years 24 - 28. The resulting whole tailings will be disposed underwater in the open pit;
- unprocessed non-PAG low-grade ore, if any, would remain in permanent stockpiles and closed in place;
- unprocessed PAG low-grade ore, if any, would be re-located for permanent subaqueous disposal in the tailings ponds;
- the rougher tailings stream will be spiggotted to the beaches adjacent to the tailings dams;
- the composition of the rougher tailings will be controlled so that they are classified as non-PAG;
- cleaner tailing are PAG and will be disposed in the centre of the tailings pond so that they permanently saturated;
- all fill required for infrastructure will be constructed from non-PAG rock; and
- the open pit will be allowed to flood at closure thereby resulting in flooding of most PAG walls. Some PAG walls will remain exposed.

6.6 Conclusions for ML/ARD Potential Characterization

The main conclusions resulting from characterization of ML/ARD potential are as follows.

- Waste rock has mixed ARD potential. Waste rock can be segregated by ARD potential at the blast scale to yield PAG and non-PAG components for separate management.
- ML potential is primarily for copper, selenium, and zinc based on the observed enrichment of these elements in the rock. Segregation by ARD potential will result in a level of control for ML potential as well; separate segregation for ML potential is not planned.
- Due to the composition of the waste rock, pit wall exposures are expected to be both PAG and non-PAG.
- Onset of ARD for PAG materials at Harper Creek appears to be very slow based on the limited development of acidic conditions in humidity cells, stored core, and overburden overlying the open pit.

- Rougher tailings are non-PAG and cleaner tailings are PAG.
- Overburden in the pit area has mixed ARD potential reflecting the presence of mineralized rock.
- Overburden outside the pit has negligible ML/ARD potential.
- The quarry designed to supply granitic rock for the coffer and starter dam construction has negligible ML/ARD potential.

REFERENCES

BC MEM. 1998a. *Policy for Metal Leaching and Acid Rock Drainage at Minesites in British Columbia*. Prepared by the British Columbia Ministry of Energy and Mines: Victoria, BC.

BC MEM. 1998b. *Guidelines for Metal Leaching and Acid Rock Drainage at Minesites in British Columbia*. Prepared by the British Columbia Ministry of Energy and Mines: Victoria, BC.

BC MEM. 2011. *MINFILE Detail Report 2011, BC Geological Survey, Harper Creek, 082M 009* http://minfile.gov.bc.ca/report.aspx?f=PDF&r=Minfile_Detail.rpt&minfilno=082M++009 (accessed April 2012).

BC MOE. 2012. *Water and Air Baseline Monitoring Guidance Document for Mine Proponents and Operators*. Prepared by the British Columbia Ministry of Environment: Victoria, BC.

Coastech Research. 1991. *Acid Rock Drainage Prediction Manual. MEND Project 1.16.1b*. Prepared by Coastech Research: West Vancouver, BC.

Ferguson, K. D. and S. M. Leask. 1988. *The Export of Nutrients from Surface Coal Mines*. Regional Program Report 87-11. Environment Canada: n.p.

Merit. 2014. *Technical Report & Feasibility Study for the Harper Creek Copper Project Near Vavenby, BC*. Prepared for Yellowhead Mining Inc. by Merit Consultants International Inc.: Vancouver, BC

Nevada Division of Environmental Protection. 1990. *Meteoric Water Mobility Procedure*. Prepared by the Bureau of Mining Regulation and Reclamation, Nevada Division of Environmental Protection: Carson City, NV.

Price, W.A. 2009. *Prediction Manual for Drainage Chemistry from Sulphidic Materials*. Report prepared for MEND Program. MEND Report 1.20.1. 579p.

Sobek A. A., W. A. Schuller, J. R. Freeman, and R. M. Smith. 1978. *Field and Laboratory Methods Applicable to Overburden and Minesoils*. USEPA Report No. 600/2-78-054, 203 pp.