ANNEXE S2QC-36

Mémo EcoMetrix - Metal Leaching Characteristics of Waste Rock and Tailings from Mine Canadian Malartic

MEMO

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Ref:	**Metal Leaching Characteristics of Waste Rock and Tailings from Mine Canadian Malartic**	Date:	16 December 2015

The objective of this memo is to provide a summary of the metal leaching characteristics of waste materials from the Mine Canadian Malartic operation with a focus on the constituents of potential concern (COPC) that represent a potential risk to water quality. A review of the comprehensive database of acid base accounting (ABA) characteristics for the waste rock, ore and tailings samples as well as the kinetic test results was completed in order to evaluate the potential risk of acid generation and to identify waste management strategies that would mitigate the acid generation and metal leaching risks.

Results from the investigations were compared to Directive 019 criteria and it was concluded that a large portion of the waste rock and the tailings were characterized as potentially acid generating. Although the rock is expected to produce acid in the long term, large lag times to the onset of acidification are expected. Carbonate depletion times for waste rock were estimated to be on the order of 20 to 200 years, while those for tailings were on the order of 100 years. Therefore, there is a long lag time expected before the potential onset of acid conditions in the absence of mitigation and this provides time and opportunity to plan and implement management strategies, during operations, for the waste rock and tailings to prevent acid generation and metal leaching in the long term.

The potential for acid generation in waste rock and tailings has been discussed and presented in detail in other documents. This memo focuses on the potential risk of metal leaching from waste rock and tailings from the Mine Canadian Malartic.

Metal Leaching Characteristics of Waste Rock

Kinetic studies, including humidity cell and column tests, were performed on samples of ore, tailings and waste rock (**Table 1**). The SGS (2014) testing included 3 samples of tailings, 2 samples of low grade ore and 5 samples of waste rock that were in operation for almost 5 years with weekly leaching cycles starting in 2008. A kinetic test program was also performed by URSTM (2013) and included humidity cell tests on 5 ore samples, 6 tailings (metallurgical test) samples, 4 waste rock samples and column tests on 7 samples consisting of 2 ores, 2 waste rock and 3 tailings samples. All of these data were reviewed and considered for estimation of drainage water quality from waste rock and tailings. The results from the five year tests on various rock types and tailings were assessed in detail to estimate loading rates and water quality associated with the active and future waste rock stockpiles and tailings storage facility at Canadian Malartic.

Table 1: Summary of kinetic tests performed on mine materials from Canadian Malartic

Material Evaluated	SGS	URSTM	
	Humidity Cell	Humidity Cell	Column
Waste Rock	5	4	2
Ore	2	5	2
Tailings	3	6	3

Leachate collected from the humidity cells, containing waste rock, exhibited neutral pH values throughout the test periods. The leachate samples from all waste rock humidity cells had measureable concentrations of sulphate and alkalinity that are consistent with results for sulphide bearing waste rock containing carbonate minerals as illustrated by the average concentrations shown under the “Humidity Cell” column in **Table 2**. The concentrations of many constituents were less than the reporting (detection) limits and the reporting limits for most constituents were as good (low) as, or better than, typical industry standards. Leachate samples associated with values of less than the reporting limit values were considered in the interpretation of risk as discussed below. For the purposes of this assessment, the average concentrations in all humidity cell leachate samples containing waste rock and low grade ore from 2013 were used to calculate the loading rates.

Reference: Metal Leaching Characteristics of Waste Rock and Tailings from Mine Canadian Malartic

Table 2: Summary of Humidity Cell and Field Loading Rates with Calculated Concentrations of COPCs in Contact Water for Waste Rock Contained Within the Stockpile at the End of Operations.

	Humidity Cell	Estimated Field Rate	Estimated Concentration in Contact Water	Dir 019 (Effluent)	MMER	Leachate Samples Less than Detection	Comments
Constituent	mg/L	g/t/a	mg/L	mg/L	mg/L	%	
Sulphate (SO4)	0.53	1.8	698				
Alkalinity (as CaCO3)	9.0	30	11855				Solubility Controlled
Calcium (Ca)	2.8	9	3669				Solubility Controlled
Aluminum (Al)	0.022	0.07	29		-/TBD	0%	Solubility Controlled
Antimony (Sb)	0.00068	0.002	0.90			27%	
Arsenic (As)	0.00037	0.001	0.5	0.2	0.5/0.1	49%	Detection Limits
Cadmium (Cd)	0.00001	0.00003	0.01			70%	Detection Limits
Chromium (Cr)	0.0005	0.002	0.7			99%	Detection Limits
Cobalt (Co)	0.00007	0.0002	0.09			16%	
Copper (Cu)	0.0006	0.002	0.8	0.3	0.3/0.05	89%	Detection Limits
Iron (Fe)	0.003	0.01	4.0	3	-/TBD	96%	Solubility Controlled
Lead (Pb)	0.00003	0.0001	0.03	0.2	0.2/0.05	35%	Solubility Controlled
Manganese (Mn)	0.009	0.03	12			0%	
Mercury (Hg)	0.00001	0.00004	0.01			96%	Detection Limits
Molybdenum (Mo)	0.0003	0.001	0.4			2%	
Nickel (Ni)	0.0001	0.0005	0.2	0.5	0.5/0.25	49%	
Selenium (Se)	0.001	0.003	1.3		-/TBD	100%	Detection Limits
Vanadium (V)	0.0001	0.0004	0.2			0%	
Zinc (Zn)	0.002	0.006	3	0.5	0.5/0.25	88%	Detection Limits

Notes:
low risk at netral pH
Moderate risk
MMER shown as current value/proposed value (0.5/0.25)
TBD - to be determined - Values are being considered for revised MMER

As a screening method to assess risk of metal leaching and water quality effects, it is useful to calculate the potential concentrations in contact water or drainage from a waste rock pile. As a first step, this was completed by assuming a configuration of the waste rock stock pile as it will be at closure, containing up to 750 Mt of rock with a height of approximately 100 m. The leaching results from the five SGS waste rock humidity cells were used to include the loading rates from all rock types that that will be present in the rock stockpile. The weighted averages of humidity cell leachate concentrations (mg/L) for each COPC were then calculated and are listed in **Table 2**. The unit loading rates from the humidity cell tests in the laboratory were converted to unit loading rates in the field (g/t/a). Then the loading rates were converted to concentrations (mg/L) in the contact water from the stockpile containing 750 Mt of rock.

The contact water concentration estimates represent the maximum potential loading conditions for the complete rock stockpile and therefore are conservative for assessing the risk of metal leaching. The chemistry of the drainage was calculated from the loadings or leaching rates from the humidity cell, adjusted for field conditions, and an estimated infiltration rate based on precipitation that is adjusted for evaporation and runoff. An annual average precipitation rate of 1000 mm/a and an infiltration factor 0.5 of precipitation were assumed for these calculations.

Adjustments in the loading rates for field conditions include a scaling factor of 0.3 for the expected temperature differences (T_f) from about 20 ^oC in the laboratory to near 0 ^oC, on average in waste rock and tailings in the field which is consistent with values reported in MEND (2006). A further adjustment factor of 0.2 was applied to the loadings values to account for differences in grain size (GS_f) between samples in the laboratory that are fine-grained and those in the field that may contain less than 20% fines that effectively control the leaching rates.

The loading calculation was completed as follows:

$$MLR_{SP} = MLR_{HC} \times H_{SP} \times \rho \times GS_f \times T_f \times Appropriate\ Unit\ Conversions$$

In which:
- MLR_{SP} = the mass loading rate per unit mass of the stockpile (g/t/a)
- MLR_{HC} = the mass loading rate for the humidity cell (mg/kg/wk)
- H_{SP} = the height of rock in the stockpile (m)
- ρ = density (t/m^3)
- T_f = is the temperature factor (unitless)
- GS_f = grain size factor (unitless)

The concentrations in the contact water (C_{cw}) were calculated as;

$$C_{cw} = MLR_{SP} / I \times \text{Appropriate Unit Conversions}$$

In which:
- I = the infiltration rate (mm/a or $m^3/m^2/a$)
- C_{cw} = the concentration in the contact water (mg/L)

This approach assumes that the loadings of constituents mix with the infiltrating water with no other chemical processes controlling concentrations. This approach is extremely conservative but provides a preliminary basis for assessing risks to water quality. In this case, the very small concentrations in the humidity cell leachate samples translate to potentially larger concentrations in the drainage or contact water as a result of the large mass of waste rock in the stockpile (**Table 2**).

Table 2 summarizes the humidity cell results and adjusted field rates together with the calculated concentrations in the contact water for the final stockpile configuration. The table also includes a reference to the number of leachate samples with concentrations reported as less than the detection limit, along with comments on probable solubility controls that may override the calculated concentrations. The Directive 019 and Metal Mining Effluent Regulation (MMER) effluent limits are also included for reference. The MMER limits include the current values on the left and proposed updated values on the right. New constituents that are being considered for effluent limits but have not yet had values proposed are noted as to-be-determined (TBD). Solubility controlled constituents are considered to represent a low risk to the receiving environment, provided the contact water remains at neutral pH.

There is some uncertainty associated with the constituent concentrations that are represented by detection limit values. For example, copper had almost 90% of the analyses reported at less than the detection limit of 0.0005 mg/L. When this value is used as the leachate concentration, the resulting calculated concentration in contact water is 0.85 mg/L. If the actual copper concentrations in the leachate samples were equal to one-tenth ($1/10^{th}$) of the detection limit or 0.00005 mg/L, the calculated concentration in the contact water would be 0.08 mg/L, a value that is less than the Directive 019 and current MMER value of 0.3 mg/L, and therefore could be considered as a low risk for water quality at the site. The COPCs with a large majority of values reported as less that the detection limits were considered as lower risk that those with the majority of concentrations from humidity cells reported as greater than the detection limits.

The calculated contact water concentrations suggest that there may be several constituents that represent a moderate risk to water quality after closure, as represented by the highlighted values in **Table 2.** The COPCs that are considered to represent moderate risks for metal leaching at the end of operations, with no mitigation, include;

- Antimony (Sb)
- Manganese (Mn)
- Molybdenum (Mo), and

Some of the constituents that were dominated by detection limit values in the humidity cell leachate samples, such as arsenic (As), copper (Cu) and selenium (Se) may also represent some risks but it is difficult to define this risk based on the available data. These risks relate to closure conditions with the complete inventory of 750 Mt of waste rock in stockpiles and not necessarily to operating conditions during the development of the rock piles when the amounts of rock will be less than the 750 Mt total.

The loadings from the waste rock that are transported by infiltration and drainage through the rock will be somewhat proportional to the mass of rock in the stockpile for those constituents that do not have solubility controls or that will not be chemically attenuated within the rock pile or along the drainage pathway. The calculated concentrations in the contact water can be prorated to the inventory of rock during the operation. During operations, the mine will be producing waste rock at a rate of approximately 50 Mt per year (**Table 3**). Therefore, the calculated concentrations can be compared to the effluent limits over time to assess potential risks as the waste rock accumulates within the stockpile during operations. The calculated concentrations in the waste rock contact water over time are summarized in **Table 3**.

Table 3: Calculated Concentrations in Waste Rock Contact Water During Operations

Year	2011	2013	2016	2020	2024	2028
Waste Rock (Mtonnes)	50	150	304	489	663	750
Constituent	mg/L	mg/L	mg/L	mg/L	mg/L	mg/L
Sulphate (SO4)	47	140	283	455	617	698
Alkalinity (as CaCO3)	790	2371	4809	7733	10486	11855
Calcium (Ca)	245	734	1488	2393	3245	3669
Aluminum (Al)	2	6	12	19	26	29
Antimony (Sb)	0.1	0.2	0.4	0.6	0.8	0.9
Arsenic (As)	0.03	0.1	0.2	0.3	0.4	0.5
Cadmium (Cd)	0.001	0.002	0.004	0.007	0.01	0.01
Chromium (Cr)	0.04	0.1	0.3	0.4	0.6	0.7
Cobalt (Co)	0.01	0.02	0.04	0.1	0.1	0.1
Copper (Cu)	0.1	0.2	0.3	0.5	0.7	0.8
Iron (Fe)	0.3	0.8	1.6	2.6	3.5	4.0
Lead (Pb)	0.002	0.007	0.01	0.02	0.03	0.03
Manganese (Mn)	0.8	2	5	8	11	12
Mercury (Hg)	0.001	0.003	0.01	0.01	0.01	0.01
Molybdenum (Mo)	0.03	0.1	0.2	0.3	0.4	0.4
Nickel (Ni)	0.01	0.04	0.1	0.1	0.2	0.2
Selenium (Se)	0.1	0.3	0.5	0.9	1	1
Vanadium (V)	0.01	0.03	0.1	0.1	0.1	0.2
Zinc (Zn)	0.2	0.5	1	2	2	3

Notes: Loadings were pro-rated to rock mass at specific years and concentrations were calculated assuming a water balance for the full footprint of the final stockpile.

If arsenic and copper are considered as water quality risks at the end of operations, for example, the results in **Table 3** suggest that concentrations may approach the Directive 019/MMER values near year 6 of the operation when about 300 Mt of rock stockpiled. In reality, the stockpile will require time to wet up to field capacity and there is typically a delay in flow as water drains from waste rock stockpiles. Therefore, the actual effects on the site runoff may be delayed beyond that time to more than 10 years into the operation. Nonetheless, these conservative estimates suggest that there may be requirements to manage water from the stockpile during the operation. Monitoring of on-site water quality will assist with water management requirements during operation. The existing water management system that captures drainage from the waste rock stockpile and routes the water to the water management pond (Bassin Sud-est) will provide adequate warning and time to implement strategies to prevent potential off-site effects.

Metal Leaching from Tailings

The results from the humidity cell tests on tailings were similar to those for the waste rock tests. Except for a few constituents, the concentrations in the leachate samples were within a factor of 2 for tailings and waste rock. The concentrations of sulphate, calcium, alkalinity and aluminum were 3 to 13 times higher in the tailings leachate samples than those observed in the waste rock leachate. Higher concentrations of sulphate, alkalinity and calcium are consistent with the higher expected rates of sulphide oxidation and neutralization for the fine grained tailings compared to the coarser grained waste rock samples tested in the humidity cells (**Table 4**).

Reference: Metal Leaching Characteristics of Waste Rock and Tailings from Mine Canadian Malartic

Table 4: Summary Humidity Cell Concentrations, Field Loading Rates and Calculated Concentrations in Tailings Runoff

	Humidity Cell	Field Rate	Final Contact Water	Dir 019 (Effluent)	MMER	Leachate Samples Less than Detection Limit	Comments
Constituent	mg/L	g/t/a	mg/L	mg/L	mg/L	%	
Sulphate (SO4)	6.74	110.9	119				
Alkalinity (as CaCO3)	25.0	411	440				Solubility Controlled
Calcium (Ca)	8.3	137	146				Solubility Controlled
Aluminum (Al)	0.094	1.5	2		-/TBD	0%	Solubility Controlled
Antimony (Sb)	0.00021	0.003	0.004			38%	
Arsenic (As)	0.00063	0.01	0.01	0.2	0.5/0.1	31%	
Cadmium (Cd)	0.00001	0.0002	0.0002			69%	Detection Limits
Chromium (Cr)	0.0005	0.008	0.01			98%	Detection Limits
Cobalt (Co)	0.0001	0.001	0.001			0%	
Copper (Cu)	0.0006	0.01	0.01	0.3	0.3/0.05	78%	Detection Limits
Iron (Fe)	0.003	0.05	0.1	3	-/TBD	81%	Solubility Controlled
Lead (Pb)	0.00002	0.0004	0.0004	0.2	0.2/0.05	37%	Solubility Controlled
Manganese (Mn)	0.012	0.2	0.2			0%	
Mercury (Hg)	0.00001	0.0002	0.0002			96%	Detection Limits
Molybdenum (Mo)	0.0003	0.005	0.01			0%	
Nickel (Ni)	0.0002	0.003	0.004	0.5	0.5/0.25	41%	
Selenium (Se)	0.001	0.02	0.02		-/TBD	93%	Detection Limits
Vanadium (V)	0.0003	0.005	0.00			5%	
Zinc (Zn)	0.003	0.04	0.0	0.5	0.5/0.25	78%	Detection Limits

Notes:
low risk at netral pH
Moderate risk
MMER shown as current value/proposed value (0.5/0.25)
TBD - to be determined - Values are being considered for revised MMER

The concentrations of the constituents were estimated in tailings contact runoff water (**Table 4**). The loading rates were adjusted for field conditions by considering only the difference in temperature between the laboratory and field. The grain sizes for tailings in the field will be the same as those in the laboratory and therefore no grain size adjustments were made for tailings. Because the tailings runoff only interacts with the uppermost 0.5 m of the tailings, the loading rates for tailings to runoff will be controlled by the oxidation and leaching reactions in that zone.

The loading rates and concentrations in the contact water were calculated as follows;

$$MLR_{tails} = MLR_{HC} \times d_{leaching} \times \rho \times T_f \times Appropriate\ Unit\ Conversions$$

In which: MLR_{tails} = the mass loading rate per unit area of tailings (g/t/a)

MLR_{HC}	=	the mass loading rate for the humidity cell (mg/kg/wk)
$d_{leaching}$	=	the depth of leaching in the tailings (m)
ρ	=	tailings dry bulk density (t/m^3)
T_f	=	is the temperature adjustment factor (unitless)

and,

$$C_{cw} = MLR_{tails} / R$$

In which: C_{cw} = the concentration in the contact water (mg/L)
R = the runoff rate (mm/a or m^3/m^2/a)

The results show that, in general, the concentrations of constituents in the contact runoff water from the tailings will not likely represent a risk at neutral pH. Leaching below the zone of oxidation in the tailings is not anticipated and therefore the seepage water quality is expected to be similar or better than that of the runoff contact water. This will be verified by testing and monitoring during operation.

Summary

Much of the waste rock and tailings at Mine Canadian Malartic are classified as potentially acid generating. However, the calculated lag times to the onset of acid generation are more than 20 years into the future as a result of the substantial quantities of carbonate minerals in the mine materials that will consume the acid produced by sulphide oxidation. Acid generation can only occur after the carbonate minerals have been depleted and are no longer available for neutralization. With the long lag times to the onset of acid generation, there will be adequate time to plan and implement mitigation strategies to prevent acid generation in waste rock and tailings.

The potential risk to water quality from metal leaching at neutral pH was also considered. A conservative loadings assessment based on the results of humidity cell tests on all rock types and on tailings was completed. The results of the assessment suggested that metal leaching from tailings at neutral pH represented a very low to negligible risk. Metal leaching results from waste rock in the complete 750 Mt stockpile suggested that there are potential risks for exceeding Directive 019 and/or MMER discharge criteria for some constituents without mitigation in place. However, the metal leaching effects, if they occur, will likely be delayed from 6 to perhaps more than 10 years into the operation. Monitoring of trends in on-site water quality will provide advance notice of metal leaching effects during the operation. The water management system on site includes capturing of waste rock drainage and routing to the water management pond (Bassin Sud-est). Monitoring results will provide adequate time to respond to metal leaching effects from the waste rock stockpile and to plan and implement water management strategies to prevent off-site effects.