Review of the Proposed Expansion of the Pigeon WRSA and Its Closure

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Summary of MDAG Recommendations to Reasonably Understand the Effects of the Proposed Expanded Pigeon WRSA on Water Contamination and Freeze-Thaw

This Review explains in detail the errors and uncertainties in the predictions of water contamination and of freezing within 8-12 years, for the proposed expansion of the Pigeon WRSA. The following compilation of recommendations comes from the findings of this Review, with supporting explanations in the respective sections.

MDAG Recommendation 2-1: The estimated future volumes of individual rock units in the Pigeon WRSA are undefined. As a result, there is no reasonable way to estimate the effects of the proposed expansion on water contamination and freezing. The Agency should request proposed volumes of individual rock units in the Pigeon WRSA

MDAG Recommendation 3-1: The thermal modelling for the currently approved and the proposed expanded Pigeon WRSA is so over-simplified as to be unreliable. Thermal modelling should be conducted in three dimensions through time, including varying solar irradiation on WRSA slopes that represent up to 90% of the WRSAs. This should be conducted for at least 500 years, as climate warming becomes more pronounced after the current limit of 100 years.

MDAG Recommendation 3-2: The thermal modelling for the currently approved Pigeon WRSA included internal heat generation through sulphide oxidation. The proposed expansion led to the same predictions of freezing within 8-12 years. This modelling and its predictions are unreliable and likely wrong, due to problems like (1) the under-estimation of the amount and duration of internal heat generation, (2) the lack of much more heat generation within the WRSA by the proposed expansion, (3) undefined tonnages of rock units, and (4) unreliable calibration of the model. Thermal modelling should be conducted in three dimensions through time, including a large range of internal heat-generation rates. This should be conducted for at least 500 years, as climate warming becomes more pronounced after the current limit of 100 years.

MDAG Recommendation 3-3: Heat movement into and through the Pigeon WRSA is, and will be, complex in three dimensions, changing at least monthly. This was simulated for the Pigeon WRSA through relatively slow, one-dimensional, vertical heat "conduction" to an overlying horizontal surface. However, Ekati WRSA data, monitoring of other waste-rock piles around the world, and basic theory point to heat "convection" as much more important. Convection would carry heat and moisture much faster and farther through the Pigeon WRSA, in complex three-dimensional patterns. As a result, the current and overly simplistic thermal modelling means predictions of freezing in 8-12 years, for the currently approved and for the proposed expanded Pigeon WRSA, are not reliable. Reasonable predictions would come from realistic, non-steady, three-dimensional thermal modelling of the proposed expansion of the Pigeon WRSA. This should include thermal convection, thermal conduction using measured thermal conductivities rather than estimates, and a range of rates for internal heat generation. An explanation is needed for why thermal conductivities of granite and schist are significantly different for Pigeon than for all other Ekati WRSAs.

MDAG Recommendation 3-4: The approved closure cover for the currently approved and the proposed expanded Pigeon WRSA involves 3 m of glacial till overlain by 1 m of granite. The glacial till is referred to as an encapsulating thermal cover, but it would be neither. At least 20% of the outer, re-sloped WRSA would not be covered by till, allowing pathways for convection. Also, the thermal modelling used higher thermal conductivities for the till than for underlying and overlying rock. This means the till cap would not provide any relative insulation to promote freezing within the WRSA. Finally, as explained in Section 6 of this Review explains, the glacial-till cap will not even be physically stable for long. Thus, any benefits of this reported encapsulating thermal cover would be relatively short lived over the centuries to millennia that it is expected to work.

MDAG Recommendation 4-1: For the Pigeon WRSA, the water balance and the amount of contamination carried by the waste-rock drainage are considered negligible. Based on visual evidence, there is little to no seepage. On the other hand, data in the closure ecological risk assessment indicated that water draining through the Pigeon WRSA is, and will be, roughly 20,000,000-70,000,000 liters/year. Approval of an expanded Pigeon WRSA should await a detailed water balance, and the monitoring of most of the drainage and contamination leaving the WRSA.

MDAG Recommendation 5-1: Because this issue of mixing granite and metasediments (schist) is important for ARD status, thermal conduction and convection, and internal heat generation, the Agency should request current and proposed volumes of individual rock units in the Pigeon WRSA.

MDAG Recommendation 6-1: The current design, and ongoing settlement of mined waste rock, indicate the buried "encapsulating" till layer would be occasionally breached, and any benefit would be degraded or lost through time. The Agency should obtain details on how the physical stability and integrity of the till layer will be maintained, monitored, and repaired through time, over at least the next few centuries.

1. Introduction

The Independent Environmental Monitoring Agency for the Ekati Minesite (the "Agency") has requested that MDAG review and comment on the proposed expansion of the Pigeon WRSA, highlighting any concerns and uncertainties that should be resolved first. The focus should be on water contamination, freezing, and thermal modelling, both in the original design and in the proposed expansion of the Pigeon WRSA. Recommendations should be made at the end of each section or subsection of the review.

According to WROMP Version 7.0 (Dominion Diamond, 2017), there have been proposed major changes to the Pigeon WRSA since the originally approved design in WROMP 4.1 (Dominion Diamond, 2014). This includes a near doubling of the tonnage of waste rock.

Appendix C of WROMP 7.0 says,

> *"The original WRSA design can accommodate 13,445,000 m^3 of waste rock; however, current mine planning requires additional storage capacity in the Pigeon WRSA. It is required that the WRSA to be expanded to incorporate an additional 11,500,000 m^3 of waste rock, for an aggregate containment volume of 24,945,000 m^3. The additional waste rock is planned to be stored in an extended area of the original WRSA."*

Unlike the recent proposal for an additional partial lift in the Misery WRSA, this expansion at Pigeon is virtually doubling the amount of sulphur-bearing, heat generating, net-acid-generating rock. As well, the footprint of the WRSA would increase from about 53 ha to about 66 ha, and its height would increase substantially, up to a height of 76 m (MDAG Table 1-1). This is a major expansion, and should be considered carefully and in detail.

MDAG Table 1-1. Comparison of Estimated Pigeon WRSA Dimensions

Parameter	Pile Dimensions[1]	Expanded Design[2]: "Original Design"	Expanded Design[2]: Pile Expansion
Height (m)	45	30-40	54-76
Length (m)	1000	1000	1060
Width (m)	600	600	710
Surface Area (m^2)	482,000	495,000	655,000
Volume (m^3)	13,445,000	13,445,000	24,956,000

[1] Data from WROMP 4.1 Appendix C.

[2] Data from WROMP 7.0 Appendix C.

Section 2.4.8 of WROMP 7.0 discusses the proposed closure cover of the Pigeon WRSA,

> *"The closure cover for the Pigeon WRSA has been designed to make use of site-specific considerations, most notably the presence of a large quantity glacial till excavated from the Pigeon pit. Glacial till mined from the Pigeon Pit that could be separated from the underlying metasediment rock has been locally stockpiled for placement as a 3 m thick encapsulating cover over the top surface and most of the sideslopes of the WRSA. A final surfacing of granite rock with a nominal 1 m thickness will be placed over the glacial till for long term stability and erosion control . . ."*

After closure, the Pigeon WRSA would have an "encapsulating" 3-m-thick glacial-till cover with 1 m of overlying granite. To be clear, Appendix C of WROMP 7.0 explained the "existing till volume" can only cover 54.7 ha, about 80% of the expanded footprint. Therefore, the "encapsulating cover" will not encapsulate the WRSA, and will not cover the outer 20% of the re-sloped WRSA. This can lead to important problems with the proposed expansion, which are discussed in the following sections.

2. Volumes of Rock Units in the Current and Expanded Pigeon WRSA

A critical aspect of all Ekati WRSAs is knowing or estimating how much of each rock unit is present in each WRSA. This is because each rock unit can affect differently: the degree of water contamination, the rate of acid generation, the rate of heat generation, etc.

I searched for relevant information on individual rock units in the Pigeon WRSA. I could find original (non-expansion) volumes, 2016-only tonnages, and tonnages mined through April 2017 (MDAG Table 2-1). Some important observations based on that information are as follows.

- The original volume estimates from resource modelling indicated the "mixed metasediments" were granite, but granite is not a "metasediment".
- At Ekati, "metasediment" is sometimes used in place of "schist", which is known to generally carry more sulphide, generate more acidity, and release more heat upon oxidation.
- Discussions of Pigeon waste rock mention mixtures of granite and metasediments, but the mined waste rock was more than 99% schist and less than 1% granite in 2016.
- The labelling and mixtures of rock units in the Pigeon WRSA across Ekati reports are confusing and contradictory.
- Pigeon schist and granite have important, but different, effects on acid generation and heat generation, as explained in later sections of this Review.

MDAG Recommendation: The estimated future volumes of individual rock units in the Pigeon WRSA are undefined, and some rock are combined together into mixtures that preclude a reasonable assessment of their internal heat generation and acid generation. As a result, there is no reasonable way to estimate the effects of the proposed expansion on water contamination and freezing. The Agency should request proposed volumes of individual rock units in the Pigeon WRSA.

MDAG Table 2-1. Estimated Materials and Volumes from the Pigeon Pit

Material[1]	In Situ "Waste-Rock" Volume (m^3)[1]	Mined in 2016 ("wet metric tonnes")[3]	Mined through April 2017 ("tonnes mined")[4]
Mixed Metasediment[2]	7,767,831 ("granite")	7,475,205 ("schist")	20,800,000
Overburden	2,313,037	414,759	4,400,000[5]
Xenolith	18,956		
Kimberlite (ore)	3,639,945	1,346,994	
Diabase	338,751	0	"na"
Waste Kimberlite	37,595	0	"na"
Granite[2]		33,935	"na"
Metasediments[2]			"na"

[1] Data from WROMP 4.1 Appendix C

[2] A footnote in 2014 says mixed metasediments were "Identified as granite in the XPAC model", but the XPAC model must be wrong. The 2016 Seepage Report showed the recent rock is mostly heat-generating schist. Similar errors in rock-unit estimates and identification have been noted elsewhere, like the 2015 Fox WRSA drilling investigation (MDAG, 2017a). WROMP 7.0 returned to calling this unseparated "mixed granite and metasediment/diabase".

[3] The 2016 Seepage Report says, "Pigeon tonnages mined in 2016 are summarized in Figure 4.1", but this should read "Table 4.1".

[4] Data from WROMP 7.0

[5] Overburden is apparently the "Surficial Material" in WROMP 7.0.

3. Thermal Modelling of the Current and Proposed Expanded Pigeon WRSA, and the Resulting Predictions of Freezing Within Roughly 10 Years

Appendix C of WROMP 7.0 explains that predictions for thermal modelling and freezing in the originally approved 2014 plan also hold, unchanged, for the expansion.

> *"A series of thermal analyses were conducted by Tetra Tech (Tetra Tech EBA 2014) to evaluate the long-term thermal behavior of the Pigeon WRSA. These analyses were carried out to verify the adequacy of the proposed closure cover, the influence of the closure cover on pile freeze-back, and the ability of the closure cover to keep the waste rock in a permafrost state. Different cases were evaluated to investigate the effects of varying cover conditions and potential heat generation from PAG material contained in parts of the WRSA. These thermal analyses were also carried out under climate change conditions for a one hundred-year period."*
>
> *"With the expansion of the Pigeon WRSA, the validity of these past thermal analyses were assessed. The volume of the Pigeon WRSA has been significantly increased from its original design; however, the conclusions from the Tetra Tech EBA 2014 thermal analysis are still valid for the new larger capacity Pigeon WRSA. This is directly attributed to the geometry of pile expansion; the major design assumptions remain unchanged. As such, the thermal behaviour of the WRSA is expected to be similar to the original design."*
>
> *"The thermal simulations of the Pigeon WRSA predict that the waste rock pile will freeze back under both scenarios with and without internal heat generation. The scenario without internal heat generation will take approximately eight years, while the scenario with internal heat will take approximately twelve years."*

As explained below, there are significant errors in the original modelling and thus also for the proposed expansion. Furthermore, additional errors and uncertainties are introduced by the proposed expansion. These are not addressed in WROMP 7.0, but should be addressed before the Pigeon WRSA expansion is considered.

3.1 Solar Heating of WRSAs

The two primary sources of heat for Ekati WRSAs are solar irradiation and internal heat generation through sulphide oxidation. Solar irradiation is discussed here, and internal heat in the next subsection.

Heat lessens the rate and extent of freezing in Ekati WRSAs, and in some cases thaws or prevents freezing in substantial portions of some WRSAs. Thus, a reasonable and precautionary assessment of heat is warranted for Ekati WRSAs.

Heat conduction and convection can re-distribute this heat within the WRSAs in complex patterns. While one-dimensional, vertical conduction has been modelled for Ekati WRSAs, realistic three-dimensional convection has not. This is discussed in more detail through this portion of the Review, particularly Section 3.3.

For solar irradiation, all thermal modelling at Ekati is based on the monthly values listed in MDAG Table 3-1 (second column). A critical observation is that solar irradiation varies substantially by month and with the slope of the WRSA surfaces.

MDAG Table 3-1. Comparison of solar irradiation (W/m²) used in Ekati thermal modelling to solar irradiation at nearby Wekweèti

Orientation of surface:	Ekati[1] not given	Wekweèti[2] South facing, vertical	South facing, ~50° tilt	Horizontal
Month		solid-filled cells: >20% higher irradiation than used in Ekati modelling ("more heat" than Ekati model); diagonally hatched cells: >20% less irradiation than used in Ekati modelling ("less heat" than Ekati model)		
January	9.1	67	54	9
February	38.7	154	134	36
March	119.5	256	250	102
April	206.4	256	295	185
May	259.7	190	262	243
June[3]	252	163	250	264
July[3]	226.4	154	232	233
August[3]	160.8	145	196	161
September[3]	124.9	124	142	93
October	41.3	71	70	40
November	14.4	57	48	13
December	3.7	34	27	4

[1] From WROMP 4.1, but identical to values in the 2016 closure ecological risk assessment.

[2] Photovoltaic and solar resource maps, Natural Resources Canada, www.nrcan.ca/18366.

[3] Average monthly air temperature above 0°C.

For example, estimated solar irradiation at Ekati is about 70 times higher in May than December. Also, for nearby Wekweèti, solar irradiation on a surface facing south at about a 50° slope is about 6 times higher than a horizontal surface in January, but slightly less than 1.0 in June and July. Vertical surfaces in May, June, and July receive substantially less solar irradiation than a horizontal surface.

Based on MDAG Table 3-1, Ekati thermal modelling is primarily applicable to horizontal surfaces. This makes sense, because Ekati thermal modelling is predominantly one-dimensional in a vertical direction. The problem is Ekati WRSAs are mostly sloping surfaces, and Table 3-1 shows that south-facing slopes can receive substantially more solar irradiation than horizontal surfaces during most months of the year.

Golder (2016), for the closure ecological risk assessment, indicated that sloped surfaces represent about 90% of the total footprint for Panda/Koala/Beartooth WRSA, about 60% of the CKRSA, about 70% for Misery, and about 30% for Fox. Sloped areas for the Pigeon WRSA were not given. Nevertheless, the planned re-sloping of the Pigeon WRSA, to accommodate the erodible glacial-till cover, would result in a large percentage of sloped surfaces for the Pigeon WRSA.

Sloping values in Table 3-1 cannot be applied directly to the large percentages of slopes of Ekati WRSAs, because many of these slopes are not south facing. In reality, some slopes would also face east, west, and north.

The preceding paragraphs show that solar irradiation of Ekati WRSAs will vary around their perimeters each hour and each month, and will vary differently across the horizontal surfaces each day and month. This creates a complex scenario of heat influx and movement in three dimensions through time. How is this complex four-dimensional scenario frequently simulated for Ekati WRSAs? One-dimensionally, along a vertical line, under a horizontal surface. This is wrong for up to 90% of Ekati WRSAs surfaces, and is invalid for predicting temperatures in the currently approved and the proposed, gradual re-sloped, expanded Pigeon WRSA.

The time- and location-varying solar irradiation creates thermal gradients around the WRSAs. In turn, this can lead to lateral and vertical thermal convection of air through waste-rock layers (discussed in more detail in Section 3.3 of this Review). This would explain why rock layers at specific depths are warming, and even unfrozen, at depth intervals of at least 5 m thick in the Panda/Koala/Beartooth, CKRSA, Fox, and Misery WRSAs. This becomes even more important after several centuries as the local climate continues to warm further.

MDAG Recommendation: The thermal modelling for the currently approved and the proposed expanded Pigeon WRSA is so over-simplified as to be unreliable. Thermal modelling should be conducted in three dimensions through time, including varying solar irradiation on WRSA slopes that represent up to 90% of the WRSAs. This should be conducted for at least 500 years, as climate warming becomes more pronounced after the current limit of 100 years.

3.2 Internal Heat Generation through Sulphide Oxidation

The preceding subsection on solar irradiation is sufficient to show that thermal modelling for the currently approved and proposed expanded Pigeon WRSA is not reliable. This subsection shows even more complexity when internal heat generation is included.

A long-term criticism of thermal modelling at Ekati is the lack of internal heat generation from sulphide oxidation, known to be important at Ekati. This criticism began before mining started, during the environmental assessment stage, and continued into 2017. Even Golder Associates recommended its inclusion in thermal modelling for the Fox WRSA in 2015 (MDAG, 2017a), but to no avail. Furthermore, the recent closure ecological risk assessment for the entire minesite in 2016 did not include internal heat generation. During the multi-agency workshop in January 2017, the company agreed to consider its inclusion, and Golder Associates thought that current humidity cells could be used for this.

However, Appendix C of WROMP 7.0 explains that internal heat generation was included in the thermal modelling of the proposed expanded Pigeon WRSA:

> *"The thermal simulations of the Pigeon WRSA predict that the waste rock pile will freeze back under both scenarios with and without internal heat generation. The scenario without internal heat generation will take approximately eight years, while the scenario with internal heat will take approximately twelve years."*

Also, Appendix C indicates internal heat generation was included in the original modelling of the approved Pigeon WRSA in 2014, but made little difference to the time to freezing (12 years vs. 8 years). WROMP 7.0 says these conclusions are "still valid" for the proposed near-double expansion.

There are no explanations of why internal heat generation was not included for other WRSAs, and not included in the important closure ecological risk assessment in 2016. There is no explanation why Dominion Diamond and Golder Associates considered adding heat generation in January 2017, when it had already added for Pigeon in 2014.

Nevertheless, Appendix C of WROMP 7.0 contains no details like:

- how heat generation was included for the expanded WRSA,
- what heat-generation rates were used for the expanded WRSA, and
- how these differed between the original design and the expanded WRSA.

WROMP 7.0 simply says,

> "*the conclusions from the Tetra Tech EBA 2014 [WROMP 4.1] thermal analysis are still valid for the new larger capacity Pigeon WRSA*".

Thus, WROMP 4.1 has to be consulted for details, (1) to figure out if nearly doubling the volume would not make a significant difference (it actually does), and (2) to determine if there are significant errors in the thermal modelling and its predictions both for the currently approved and the proposed expanded WRSA. Based on my review of WROMP 4.1, I find thermal modelling for both the currently approved and the proposed expanded Pigeon WRSA is unreliable.

Section 3.9 of WROMP 7.0 explains that all rock from the Pigeon Pit has detectable sulphur. This rock is thus capable of significant and sustained heat generation, which would reduce internal freezing of the WRSA. Figure 3.3 confirms that some rock will generate acidic conditions, which can accelerate further the rate of internal heat generation. The following subsections explain how this information was not correctly incorporated into the thermal modelling.

3.2.1 Thermal modelling under-estimated the amount of heat-generating sulphur in Pigeon waste rock

WROMP 4.1 explained,

> *"Acid-Base Accounting (ABA) results of the waste rock yielded a mean sulphur content of 0.052% in the mixed metasediment and 0.05% in the diabase material."*

These relatively low amounts of sulphur would generate relatively low amounts of heat, allowing freezing to occur faster. The problem is that much of the Pigeon rock contains more sulphur, and would thus generate much more heat than modelled. The proposed expansion further increases the amount of heat generated, and thus the expansion would lead to different predictions. This contradicts the conclusion in WROMP 7.0.

Although some rock-unit names are confusing, Table 7.1 in the 2016 Seepage Survey showed that Pigeon Schist contained an average sulphur level of 0.1%S through 2010-2016. MDAG Table 2-1 above showed that more than 99% of the Pigeon waste rock in 2016 was this higher-sulphur-bearing schist. Table 7.1 also showed Pigeon Granite in 2016 contained an average of 0.14%S. Thermal modelling of the original plan in 2014 and the expanded plan in 2017 used only 0.05%S. Thus, internal heat generation was under-estimated for the Pigeon WRSA and there would be less cooling and freezing than predicted for the expansion.

3.2.2 Thermal modelling under-estimated the duration of heat-generating sulphur oxidation in Pigeon waste rock

WROMP 4.1 makes nonsensical statements, with no supporting evidence, about the duration of sulphide oxidation and internal heat generation. As explained in MDAG (2017a and 2017b), some of this nonsense can be traced to misunderstandings at Ekati about "non-acid generating" rock incorrectly being considered "un-reactive" and "weakly reactive".

> *"This is a conservative approximation since sulphur within the interior of the rock rarely reacts in non-acid generating systems."*

Another nonsensical statement says oxidation is complete within 40 weeks and this time frame is "typical".

> *"Assuming the sulphur oxidation is completed within 40 weeks (which is a typical timeframe in non-acid generating systems) . . ."*

These statements are wrong. The absence of heat generation after 40 weeks in the Pigeon thermal modelling at least partially explains the invalid predictions of freezing in 8 years with no heat production, and in 12 years with internal heat generation.

Therefore, all thermal modelling, and associated predictions of freezing in 8-12 years, are wrong, for both the currently approved and the proposed expanded Pigeon WRSA.

3.2.3 Incorrect rock units were used in the thermal modelling of Pigeon waste rock

As a preceding quotation said, thermal modelling was based on "mixed metasediment" and "diabase". As indicated in MDAG Table 2-1, by far most of the recent Pigeon waste rock is schist, although WROMP 7.0 failed to provide cumulative tonnages of each rock unit.

Thus, thermal modelling of the currently approved Pigeon WRSA is not reliable, because it did not reflect the rock units placed in the WRSA. Because the proposed expansion said there was no change in the results of thermal modelling, it also is based on incorrect amounts of rock units. Notably, WROMP 7.0 does not even estimate the tonnages of each rock unit for the expansion - just saying there is no change to the thermal predictions.

3.2.4 Unreliable calibration of the thermal modelling to Pigeon waste rock

Section 5.0 of Appendix C of WROMP 4.1 explains how the thermal model, that included internal heat generation, was calibrated to Pigeon waste rock - it was not. It was calibrated to "OP-01", which was not explained or identified.

According to Table 5 of Appendix C, OP-01 apparently:

- (1) contained no waste rock, unlike the Pigeon WRSA,
- (2) was completely frozen from top to bottom, unlike the Pigeon WRSA and the other WRSAs, and
- (3) generated no internal heat, unlike Ekati waste rock.

Yet, this was taken as valid calibration to predict freezing of the Pigeon WRSA within 8-12 years, for both the currently approved and the proposed expanded Pigeon WRSA. As shown in the previous subsections, predictions of freezing in the Pigeon WRSA are unreliable. It is currently unknown how much, if any, freezing will occur in the current and proposed expanded Pigeon WRSA.

MDAG Recommendation: The thermal modelling for the currently approved Pigeon WRSA included internal heat generation through sulphide oxidation. The proposed expansion led to the same predictions of freezing within 8-12 years. This modelling and its predictions are unreliable and likely wrong, due to problems like (1) the under-estimation of the amount and duration of internal heat generation, (2) the lack of much more heat generation within the WRSA by the proposed expansion, (3) undefined tonnages of rock units, and (4) unreliable calibration of the model. Thermal modelling should be conducted in three dimensions through time, including a large range of internal heat-generation rates. This should be conducted for at least 500 years, as climate warming becomes more pronounced after the current limit of 100 years.

3.3 Heat Conduction and Convection through Pigeon Waste Rock

As discussed above in Sections 3.1 and 3.2 of this Review, heat movement into and through the Pigeon WRSA would be complex in three dimensions, changing hourly and monthly. This was simulated for the Pigeon WRSA as one-dimensional vertical heat conduction to a horizontal surface.

This overly simplistic modelling means predictions of freezing, for the currently approved and for the proposed expanded Pigeon WRSA, are not reliable.

Heat moves into and through Ekati WRSAs in two primary ways. First, through relatively slow "conduction", heat is transferred through the solid phases of rock, water, and ice. Second, through relatively fast "convection", air moves in complex patterns through pore spaces in waste-rock dumps, carrying heat and moisture. Convection has been observed in many waste-rock dumps, including those in permafrost environments (e.g., Dawson and Morin, 1996), and especially in those with heat-generating sulphide like Ekati (e.g., Morin et al., 1991; Lefebvre et al., 1994; and Morin and Hutt, 1997).

Convection would be important for the Pigeon WRSA. This is because, even after closure, the outer 20% of the WRSA would have not a till cover (see Sections 1 and 6 of this Review), providing coarse-rock open passages for air to enter and exit in three dimensions.

How was faster-moving convection simulated in the one-dimensional thermal modelling of the currently approved and proposed expansion of the Pigeon WRSA? It was not - that is impossible. Air currents would need to enter somewhere and exit somewhere. The Pigeon thermal modelling, starting at the bedrock and extending upwards to a horizontal surface, cannot simulate convection. Again, this overly simplistic modelling means predictions of freezing for the currently approved, and the proposed expanded, Pigeon WRSA are not reliable.

Heat conduction would not likely determine freezing and thawing within layers of the Pigeon WRSA since convection would be dominant. Nevertheless, it is worthwhile to check how conduction was modelled in Ekati WRSAs.

An important parameter for simulating heat conduction is thermal conductivity, which represents the ease and rate at which heat can move through rock, water, and ice. As explained in detail in MDAG (2017b), thermal conductivities used for Ekati rock were guesses, using guesses of rock porosity with an unreliable equation to obtain thermal conductivities. In contrast, the 2015 Fox Geotechnical Investigation (MDAG, 2017a) was closer to reality by examining quartz contents of the rock units, rather than porosity (Eppelbaum et al., 2014). Overall, thermal conductivities should be measured in Ekati rock, instead of these unreliable guesses and estimates.

The comparisons of thermal conductivities assumed for the Pigeon thermal modelling, to those assumed for modelling of all WRSAs in the closure ecological risk assessment (Closure ERA), lead to interesting observations (MDAG Table 3-2).

- For the Pigeon WRSA (currently approved and proposed expansion), the thermal conductivity of the waste rock was assumed to be 1.07 W/m°C frozen and 1.27 W/m°C unfrozen. As explained in Section 2 of this Review, most of the Pigeon waste rock is schist and granite. In contradiction, all thermal modelling for the Closure ERA used significantly lower conductivities for schist and most granite, which were given similar values. Why do all other WRSAs, except Pigeon, have about the same thermal conductivities for these rock units? It raises the possibility that Pigeon waste rock was incorrectly modelled thermally.

MDAG Table 3-2. Comparison of Thermal Conductivities (W/m°C) Used in Thermal Modelling at Ekati

Material	WROMP 4.1, Used for Pigeon Frozen	WROMP 4.1, Used for Pigeon Unfrozen	Closure ERA[1] Frozen	Closure ERA[1] Unfrozen
Till, Thawed	2.43	1.98		
Till, Ice Rich, Frozen	2.53	1.28		
Till, Frozen	2.23	2.23		
Bedrock	3.00	3.00		
Bedrock			3.00	3.00
Overburden Till	1.87	1.72		
Glacial Till			2.18	1.84
Clean Waste Rock	1.07	1.27		
Waste Rock	1.07	1.27		
Coarse PK			1.60	1.20
Schist Waste Rock			0.63	0.83
Kimberlite Waste Rock (Lower Fox)			2.17	1.38
Kimberlite Waste Rock (Upper Fox)			1.47	1.17
Granite Waste Rock (Panda/Koala, CKRSA, and Misery)			0.71	0.89
Granite Waste Rock (Lower Fox)			1.11	1.36
Granite Waste Rock (Upper Fox)			0.72	0.80

[1] The Closure Ecological Risk Assessment did not include any effects or impacts for Pigeon.

- In both modelling efforts, the thermal conductivities of till (thawed), till (frozen), overburden till, and glacial till are all higher than the rock units in the Pigeon WRSA. The important implications of this are discussed in Section 3.4 of this Review.

Although heat convection was not modelled in the Pigeon WRSA, it apparently is considered important for freezing and thawing. Section 2.4.8 of WROMP 7.0 on the Pigeon WRSA says "coarser and harder" rock particles enhance freezing:

> *". . . the inclusion of granite within the mixed materials provides coarser and harder particles that can be expected to enhance permafrost aggradation into the WRSA by maintaining physical conditions that are more favourable to heat transfer."*

Such coarser particles enhance convection, not conduction, which could enhance freezing, or heating, in the Pigeon WRSA as the climate continues to warm. However, convection was not modelled, so there is no way to estimate its likely great importance. Yet, the quotation suggests convection is critical to predictions of freezing in the Pigeon WRSA. This is another reason that the predictions of freezing within 8-12 years, in the currently approved and proposed expanded, Pigeon WRSA are unreliable.

The alternative explanation to that quotation says it is talking about conduction rather than convection. That would be a major problem. Thermal modelling for the closure ecological risk assessment in 2016 assumed the thermal conductivity of granite was significantly less than kimberlite (MDAG Table 3-2), and thus granite could not "enhance permafrost aggradation".

If that quotation above from WROMP 7.0 refers to convection, then thermal modelling for the Closure ERA is wrong. This would agree with the findings in this Review and MDAG (2017b). If it refers to conduction, it is still wrong. The 2015 Fox Geotechnical and Geochemical Studies (MDAG, 2017a) would agree with WROMP 7.0 that convection is important, and thus disagree with the 2016 Closure ERA.

In any case, during ongoing climate warming during centuries and millennia into the future, the more thermally conductive and convective granite will not "enhance permafrost aggradation into the WRSA". Instead, it will allow increasing warmth to reduce and reverse any permafrost formation more rapidly.

MDAG Recommendation: Heat movement into and through the Pigeon WRSA is, and will be, complex in three dimensions, changing at least monthly. This was simulated for the Pigeon WRSA through relatively slow, one-dimensional, vertical heat "conduction" to an overlying horizontal surface. However, Ekati WRSA data, monitoring of other waste-rock piles around the world, and basic theory point to heat "convection" as much more important. Convection would carry heat and moisture much faster and farther through the Pigeon WRSA, in complex three-dimensional patterns. As a result, the current and overly simplistic thermal modelling means predictions of freezing in 8-12 years, for the currently approved and for the proposed expanded Pigeon WRSA, are not reliable. Reasonable predictions would come from realistic, non-steady, three-dimensional thermal modelling of the proposed expansion of the Pigeon WRSA. This should include thermal convection, thermal conduction using measured thermal conductivities rather than estimates, and a range of rates for internal heat generation. An explanation is needed for why thermal conductivities of granite and schist are significantly different for Pigeon than for all other Ekati WRSAs.

3.4 Glacial Till as an "Encapsulating" "Thermal" Cover

Section 2.4.8 of WROMP 7.0 points out the approved glacial-till cap would be encapsulating:

> *"Glacial till mined from the Pigeon Pit that could be separated from the underlying metasediment rock has been locally stockpiled for placement as a 3 m thick encapsulating*

cover over the top surface and most of the sideslopes of the WRSA."

However, Appendix C of WROMP 7.0 explained the "existing till volume" can only cover 54.7 ha, about 80% of the expanded footprint. Thus, the outer 20% of the Pigeon WRSA would not be "encapsulated". As explained in the previous subsections, this provides pathways for heat convection through the Pigeon WRSA, which were not included in the overly simplistic and invalid thermal modelling of the proposed expansion.

Also, Appendix C of WROMP 7.0 states,

> *"The proposed cover for the original WRSA comprises till overburden soil overlain by clean granite. This will provide thermal cover while reducing the required quantity of clean NAG granite."*

Therefore, the partial glacial-till cap will be a "thermal cover". This wording apparently means the till would hold freezing conditions within the Pigeon WRSA. However, it could do just the opposite - it could hold the internally generated heat, substantially increased by the near doubling of heat-generating waste rock. In turn, this would maintain unfrozen conditions within the WRSA, despite current overly simplified and invalid predictions of freezing in 8-12 years.

Most important, in both modelling efforts for the currently approved and the proposed expanded Pigeon WRSA, the thermal conductivities of till (thawed), till (frozen), overburden till, and glacial till are all higher than the rock units in the Pigeon WRSA (MDAG Table 3-2). As a result, the thermal modelling could not have shown the till cap was an encapsulating thermal cover, but instead a more heat-conductive layer. Thus, the thermal modelling of the proposed expansion must be wrong since it showed the glacial-till cap as a thermal cover.

Finally, as Section 6 of this Review explains, the glacial-till cap will not even be physically stable for long, but will collapse and settle through time. If the till cap is somehow an encapsulating thermal cover, its effects will be relatively short term compared to the centuries to millennia that it is expected to work.

MDAG Recommendation: The approved closure cover for the currently approved and the proposed expanded Pigeon WRSA involves 3 m of glacial till overlain by 1 m of granite. The glacial till is referred to as an encapsulating thermal cover, but it would be neither. At least 20% of the outer, re-sloped WRSA would not be covered by till, allowing pathways for convection. Also, the thermal modelling used higher thermal conductivities for the till than for underlying and overlying rock. This means the till cap would not provide any relative insulation to promote freezing within the WRSA. Finally, as explained in Section 6 of this Review explains, the glacial-till cap will not even be physically stable for long. Thus, any benefits of this reported encapsulating thermal cover would be relatively short lived over the centuries to millennia that it is expected to work.

4. Current and Proposed Expanded Releases of Potentially Contaminated Water from the Pigeon WRSA into the Surrounding Environment

How much water passes through the Pigeon WRSA and into the surrounding subsurface and surface environment? How much would pass through an expanded Pigeon WRSA? These are important questions, because all this water accumulates contaminants as it flows through the waste rock.

Contamination and release of drainage waters from the Pigeon WRSA are said to be virtually zero in WROMP Version 7.0:

> *"No seepage was observed during the 2015 freshet seepage survey, and one seep was observed and sampled during the fall 2016 seep survey. Seep sampling will continue to be monitored during the fall survey and in subsequent years."*

And

> *"There will be no perceivable 'flow' of water through the base of the WRSA because of the limited catchment area and, importantly, because of the aggradation of permafrost in the base of the WRSA."*

Similarly, Section 7.4 of the 2016 seepage survey says,

> *"Seepage from the Pigeon WRSA was found in just one location in 2016. Prior to 2016 there had been no seepage from the WRSA and therefore no sampling stations had been previously established at Pigeon."*

Thus, there is reportedly little to no flow. However, this is based on visual evidence only. There is no water-monitoring instrumentation in the subsurface active layer. Is this a case of "out of sight, out of mind"?

The "limited catchment area" of the Pigeon WRSA itself will be approximately 50-70 ha, which is the smallest footprint of the Ekati WRSAs. Based on minimum and maximum infiltration rates used in the 2016 closure ecological risk assessment, this means 20,000-70,000 m^3/yr (20,000,000-70,000,000 liters/year) will move through the WRSA. The other WRSAs would have much higher seepage rates (tabulated in MDAG, 2017a).

Although 20,000,000-70,000,000 liters/year may not be "perceiveable" to humans, it is a major release of contaminated water to the surrounding environment. How contaminated is all this water? For a single surficial seep seen in 2016, with a flow of 3 L/s, Section 7.4 of the 2016 seepage survey explained,

> *"Pigeon seepage is not compared to the Water Licence effluent quality criteria as seepage drains to a pond that then drains to the LLCF."*

What about the remainder of the 20,000,000-70,000,000 liters/year? Did it have the same contaminant concentrations, or did it vary with location?

Additionally, as explained above in this letter, there is no reliable expectation that the Pigeon WRSA will freeze entirely and remain so for a long time. In fact, internal heat generation and quartz-rich rock suggest it will not freeze. So, any future hopeful reduction in seepage (less than 20,000,000-70,000,000 liters/year) attributed to freezing is unreliable and could be wrong.

MDAG Recommendation: For the Pigeon WRSA, the water balance and the amount of contamination carried by the waste-rock drainage are considered negligible. Based on visual evidence, there is little to no seepage. On the other hand, data in the closure ecological risk assessment indicated that water draining through the Pigeon WRSA is, and will be, roughly 20,000,000-70,000,000 liters/year. Approval of an expanded Pigeon WRSA should await a detailed water balance, and the monitoring of most of the drainage and contamination leaving the WRSA.

5. Unreliable Mitigation of ARD Potential in the Current and Proposed Expansion of the Pigeon WRSA

Section 2.4.8 of WROMP 7.0 says,

> *"Therefore, for waste rock management purposes, all of the mixed granite and metasediment waste rock is to be managed as if it were PAG material (i.e., encapsulation within a thermally protective cover). This approach provides a conservative element to the long-term performance of the Pigeon WRSA since the geochemical characterization shows that a granite/metasediment mixture in the range of 30-70% metasediment can be classified as NAG (i.e., non-acid generating)."*

This quotation is ambiguous and may be unreliable.

If "*granite/metasediment mixture in the range of 30-70% metasediment*" means in-situ rock being mined, there is no such mixture currently reported in the Pigeon WRSA (see MDAG Table 2-1 for summary of rock units). Lately, more than 99% of waste rock has been schist.

If "*granite/metasediment mixture in the range of 30-70% metasediment*" represents anticipated mixing or layering within the WRSA, it is unreliable for ARD mitigation. Such mixing or layering is not considered reliable mitigation in Canada, unless carefully and thoroughly proven, which has not been done for Pigeon waste rock.

Furthermore, mixing at Ekati is based on the often-wrong assumption that 100% of measured neutralization potential is available and reactive under field conditions, which even Dominion Diamond knows is wrong (see MDAG, 2017a). Under typical field conditions, most Pigeon rock would be considered net acid generating.

All this might be unimportant, because all of the mixed granite and metasediment will be reportedly managed as if it were "PAG" (net acid generating), and large portions in recent years seem to be so. On the other hand, it must be important. The ARD status of the mixture and individual rock units are discussed in detail with abundant supporting data, to point out much of the range will be net acid neutralizing ("NAG"), which data show is mostly incorrect. So, it is both important and not important.

In reality, the differentiation of Pigeon rock units and their associated physical, geochemical, and thermal characteristics are important. This has been shown in the previous sections of this Review.

MDAG Recommendation: Because this issue of mixing granite and metasediments (schist) is important for ARD status, thermal conduction and convection, and internal heat generation, the Agency should request current and proposed volumes of individual rock units in the Pigeon WRSA.

6. Physical Stability of the Closure Cover for the Pigeon WRSA

The approved closure cover for the expanded Pigeon WRSA is 3 m of glacial till placed over Pigeon waste rock, overlain by 1 m of granite. As proposed and depicted (e.g., Figure 6 of Appendix C of WROMP 7.0), the very fine-grained till will be placed directly over coarser waste rock.

WROMP 7.0 explains in detail how the slopes of the Pigeon WRSA would be re-sloped, unlike all other WRSAs, to more gradual, less step-like, slopes. This would minimize the surficial erosion of water running downslope on top of the glacial till.

However, this resolved only one of the three failure mechanisms that would rupture the "encapsulating" cover. The other two mechanisms of failure are: collapses of fine-grained glacial till downwards into underlying waste rock due to (1) differences in particle sizes, and (2) ongoing settlement and breaking of waste rock.

First, the approved cover design has no gradation layer between the till and the underlying waste rock. In other words, the finer-grained till will likely collapse and migrate downwards into the underlying coarser waste rock through time. With time, the till layer will no long be a layer, and the predicted benefits of the "encapsulating" till layer will be degraded or lost.

Secondly, mined waste rock typically settles and breaks and weathers on an ongoing basis, long after mining. The rates are typically faster than weathering of long-exposed rock and boulders at the earth's surface into soil, due to factors like blasting-and-fracturing, release of compressive stresses, and rapid reaction of newly exposed mineral and rock surfaces.

As a result, the till layer cannot remain intact in the long term without repairs, but will sag, perforate, and collapse in places. These ruptures may be difficult to see beneath 1 m of granite. In turn, over the next several centuries, this means repairs to the till layer beneath 1 m of granite could be expensive, time consuming, and difficult.

MDAG Recommendation: The current design, and ongoing settlement of mined waste rock, indicate the buried "encapsulating" till layer would be occasionally breached, and any benefit would be degraded or lost through time. The Agency should obtain details on how the physical stability and integrity of the till layer will be maintained, monitored, and repaired through time, over at least the next few centuries.

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