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# Summary of Potential Impacts of Taconite Tailings Disposal in the Minorca Pit on Water Quality in the Missabe Mountain Pit

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Report to Rebecca Wooden September 2, 1999

Minnesota Department of Natural Resources Division of Lands and Minerals

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#### 1. Introduction

At current production levels, Ispat Inland Mining Company's (Inland) taconite operation near Virginia, Minnesota will exceed the capacity of their tailings basin in approximately four years. As an alternative to expanding the existing tailings basin, Inland has proposed disposing of both fine and coarse tailings in the Minorca Pit. The Minnesota Pollution Control Agency (MPCA) may issue permits for in-pit disposal of taconite tailings if it can be shown "that the deposition of tailings will not pose an unreasonable risk of pollution or degradation of ground water" (Laws of Minnesota, 1996, Chapter 407, Section 56). There is a specific concern for the potential impact that tailings disposal in the Minorca Pit may have on the drinking water supply for the city of Virginia, because of the close proximity of the Minorca Pit and the complex geology and hydrology of the area.

The Minnesota Department of Natural Resources (MN DNR) and the University of Minnesota (U of MN) have been studying the potential water quality implications of disposal of taconite tailings in existing mine pits across the Mesabi Iron Range (Berndt and Lapakko, 1997a, b; Berndt 1998; Berndt et al, 1998, 1999). Results from this study on tailings pore water chemistry were used by the Minnesota Department of Health (MDH) to conduct a health risk assessment for Inland's proposal (MDH, 1998). Their assessment focused on potential risks to human health, and did not consider secondary drinking water quality standards. The present assessment focuses on impacts of output from the Minorca Pit clear water pool and tailings pore water on water quality in the Missabe Mountain Pit with respect to primary and secondary drinking water quality standards. It also identifies chemical reactions that may reduce the levels of potential contaminants in local ground waters.

As the responsible governmental unit for the proposal, the MN DNR is currently preparing a supplemental environmental impact statement (SEIS) for Inland's proposal to dispose of taconite tailings in the Minorca Pit rather than expand the existing tailings basin. This document summarizes aspects of the MN DNR/U of MN study that are directly related to the SEIS. Although several taconite operations across the Mesabi Iron Range participated in this study, the information presented in this document will focus primarily on operational measurements and controlled experiments using tailings and process waters from Inland. Data from other operations were used, in conjunction with those from Inland, to describe environmentally relevant chemical reactions associated with taconite tailings and the water which they contact.

This document summarizes findings relevant to the impact of tailings disposal in the Minorca Pit on concentrations of Mn, F, Mo, and As in the Missabe Mountain Pit. More detailed information on this assessment (Lapakko and Jakel, 1999) as well as the MN DNR/U of MN range-wide study (Berndt and Lapakko, 1997a,b; Berndt, 1998; Berndt et al., 1998, 1999) are available through the MN DNR, Division of Lands and Minerals, Saint Paul, MN (651-296-4807 or 1-800-766-6000 in Minnesota).

#### 2. Site Description

Inland's taconite processing operation is located approximately two miles northeast of Virginia, MN (Figure 1). The Minorca Pit lies approximately 0.5 miles south of Inland's taconite processing plant. At present, the water table in the Minorca Pit is at approximately 1400 feet mean sea level (m.s.l.), which may be as much as fifty feet lower than that of the adjacent ground water (Adams, 1998; MDH, 1998). Consequently, the pit acts as a hydrologic sink for surrounding ground water. Inland currently maintains the pit water level by pumping excess water to the Sauntry Creek at an average rate of 1419 gpm (Indeco, 1999).

The proposed action would involve pumping coarse and fine tailings slurried with process water from the processing plant to the Minorca Pit. Tailings settle to the pit floor creating a clear water pool. Some of the water from this pool will continue to be used to augment stream flow in the Sauntry Creek. Much of the water remaining in the clear pool will be pumped back to the plant for reuse.

After five years of tailings and process water deposition, the water level in the Minorca Pit is expected to reach the estimated water level, 1450 feet m.s.l. (Indeco, 1999). This will result in ground water outflow from the Minorca Pit into the Biwabik aquifer. The primary source of outflow is expected to be from the clear water pool until the tailings elevation reaches the lowest pit rim elevation (1470 feet m.s.l.). It is anticipated that once Inland begins to deposit tailings into the Minorca Pit, the tailings elevation will reach 1470 feet in approximately eight years (Indeco, 1999). Thus, the period during which Minorca Pit ground water outflow may be dominated by the clear water pool is estimated to be between years five and eight. After the tailings elevation reaches 1470 feet m.s.l., ground water outflow from the pit will be dominated by tailings pore water (i.e. all ground water output from the pit to surrounding ground water will be from tailings pore water). The pit is expected to reach its capacity ten years after disposal begins. At this time the surface will be prepared for vegetation.

The elevation at which ground water outflow from the Minorca Pit is anticipated is approximately 230 feet higher than the current water level in the Missabe Mountain Pit, which is used as the drinking water supply for the city of Virginia. Because of the complex geology in the area, the possibility of a hydrologic connection between these two pits cannot be ignored. In order to provide the most conservative estimate of the potential water quality impacts of disposal of tailings in the Minorca Pit, it was assumed that ground water outflow from the Minorca Pit will reach the Missabe Mountain Pit.

#### 3. Approach

Out of more than 162 inorganic elements and organic compounds examined in waters associated with taconite tailings during the range-wide study (Berndt and Lapakko, 1997a), only five inorganic elements were identified as approaching or exceeding drinking water quality standards.

Of these five, three (manganese, fluoride, and molybdenum) were found to approach or exceed drinking water quality standards at Inland's operation. A fourth element, arsenic, has been reported to the MPCA at levels as high as 18 ug/L as part of the National Pollution Discharge Elimination System (NPDES) program. Although this value did not approach the existing drinking water quality standard of 50 ug/L, arsenic was included in this assessment because the US EPA is considering lowering the drinking water quality standard in January 2001. These four elements will be referred to collectively as elements of concern, or ECs.

This document will describe EC concentration changes in the Missabe Mountain Pit which could result from taconite tailings disposal in the Minorca Pit. Each EC will be discussed individually with regard to expected levels in flow leaving the Minorca Pi (source terms), transport through the aquifer, and dilution and chemical reactions in the Missabe Mountain Pit (Figure 2).

#### 3.1. Minorca Pit Source Terms

Currently, the Minorca Pit acts as a sink for ground water, precipitation and runoff from the surrounding area resulting in an average water level in the pit of approximately 1400 feet m.s.l. (MDH, 1998). If the Minorca Pit is filled with tailings, ground water outflow may take place once the water level reaches approximately 1450 feet m.s.l. (Adams, 1998). "Source term" refers to the range of expected EC concentrations in waters leaving the Minorca Pit. This term includes waters exiting the Minorca Pit from the clear water pool as well as tailings pore waters. Source terms become important as soon as the water level in the pit reaches that of the surrounding ground water and the ground water gradient reverses. As described earlier, we anticipate that the clear water pool maintained in the Minorca Pit will influence outflow water chemistry between the fifth and eighth year after tailings deposition begins.

As the pit continues to fill with tailings and process water, conditions within the tailings mass will become less oxidizing. As the environment changes, chemical reactions between process water and tailings will change the composition of tailings pore waters within the Minorca Pit. Consequently, the quality of water observed in plant discharges is not always a good indication of tailings pore water source terms for the Minorca Pit. In order to determine appropriate source terms for each EC, it was necessary to examine the water chemistry resulting from tailings-water interactions in an environment isolated from the atmosphere. Source terms for each EC were determined by the concentration ranges for plant discharges, tailings pore waters collected from Inland's tailings basin, as well as field and laboratory experiments using tailings from Inland's operation.

#### 3.2. Transport in the Biwabik Aquifer

As ground water flows out of the Minorca Pit, dissolved ECs may ultimately be transported to the Missabe Mountain Pit. The geology of the Biwabik Iron Formation is extremely complex with folded and fractured rocks, numerous fault zones, and abandoned mine pits. Each of these features affects the path of ground water flow within the Virginia Horn area.

Due to the complex hydrology, the flow time from the Minorca Pit to the Missabe Mountain Pit has not been quantified. A rigorous analysis of hydraulic conductivities in the area would be extremely difficult to develop due to the unknown frequency, dimensions, and location of fractures through which flow is transmitted. However, some generalizations about ground water flow may be useful.

Ground water flow depends on the hydraulic conductivity of the host rock. Flow through bedrock in the Biwabik Iron Formation has been estimated at 0.7 to 1.8 feet/day (HDR, 1997). At this rate, ground water leaving the Minorca Pit and flowing through intact bedrock will reach the Missabe Mountain Pit (4650 feet away) in 7 to 18 years. If a direct connection exists via fractures in the bedrock, flow times between the two pits may be reduced to months, or even weeks. These generalizations do not precisely quantify the length of time required for Minorca Pit waters to flow to the Missabe Mountain Pit, but rather roughly estimate the upper and lower bounds for the flow time.

To determine the highest possible impact of taconite tailings in the Minorca Pit on Missabe Mountain Pit water quality, it was assumed that the pits are hydrologically connected (i.e. water can flow between them). Furthermore, it was assumed that all of the ground water exiting the Minorca Pit reported to the Missabe Mountain Pit within a short time frame. This assumption has not been verified (MDH, 1998), and may affect the timing of impact on the Missabe Mountain pit. For example, if the flow time between pits is ten years, then the maximum concentrations in the Missabe Mountain Pit presented in this document are projected to occur ten years too soon.

Although ground water from the Minorca Pit may not react as it flows through the aquifer, it is more likely that Minorca Pit waters will react with the host rock and water in the Biwabik aquifer. Such reactions may affect EC levels. Based on the predicted chemistry of water leaving the Minorca Pit, measured water chemistry of the Biwabik aquifer, and minerals known to be present in the Biwabik Iron Formation, geochemical controls on EC levels during transport were determined. These calculations were used to predict the most likely EC levels in the Minorca Pit ground water as it enters the Missabe Mountain Pit.

#### 3.3. Concentration Changes in the Missabe Mountain Pit

Present EC concentrations in Missabe Mountain Pit water are low, and meet drinking water quality standards. Flow from the Minorca Pit will contain elevated EC concentrations and its input to the Missabe Mountain Pit will tend to elevate aqueous concentrations in the pit. The extent to which concentrations are elevated will depend on the extent of dilution and EC removal by chemical reaction.

EC concentrations in Minorca Pit input will be diluted by other inputs to the Missabe Mountain Pit and the water initially present in the Missabe Mountain Pit. The other inputs to the Missabe Mountain Pit are precipitation and ground water from sources other than the Minorca Pit. These

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dilutional flows will persist over time. Based on the magnitudes of the impacted and dilutional flows and their quality, flow-weighted average input EC concentrations were calculated. These values were used by MDH for their Health Risk Assessment (MDH, 1998). The volume of water stored in the Missabe Mountain Pit will also provide dilution, although the duration of its impact is shorter. This volume and the associated water quality were considered in the calculation of predicted EC levels in this pit.

In addition to dilution, oxidizing conditions in the Missabe Mountain Pit may promote chemical reactions that further decrease EC levels. Therefore, geochemical controls on EC levels in the Missabe Mountain Pit were examined.

These hydrological and geochemical calculations provided a range of EC levels that can be expected in the Missabe Mountain Pit if taconite tailings are disposed of in the Minorca Pit. Since the Missabe Mountain Pit serves as the drinking water supply for the city of Virginia, the expected EC ranges were compared to existing primary and secondary drinking water quality standards. Any exceedence of these standards could result in water supply treatment issues for the city Public Utility.

### 4. Data Collection, Calculations and Analytical Methods

The methods used during this study have been described in detail elsewhere (Berndt and Lapakko, 1997a, b; Berndt, 1998; Berndt et al., 1998, 1999; Jakel et al., 1998; Jakel and Lapakko, 1999 a, b,c). These methods are summarized here in order to illustrate the approach used in this document.

#### 4.1. Minorca Pit Source Terms

#### 4.1.1. Clear Water Pool Source Term

Operational field measurements of EC levels in waters closely associated with taconite tailings have been collected over a two and a half year period (Berndt and Lapakko, 1997a; Berndt et al., 1998, 1999). Ten water samples were collected at the point at which Inland discharges tailings and process water into the tailings basin. Since ECs are released during taconite processing, EC levels in process waters tend to increase over time. Therefore, concentrations of components which are not removed from solution by chemical precipitation or adsorption (e.g. F, Mo) tend to increase as water recycles through the plant (Berndt and Lapakko, 1997a). If such increases occur, the degree to which they occur depends on the amount of dilutional water (i.e. make-up water) introduced to the processing stream.

During the first two years of tailings deposition in the Minorca Pit, the amount of dilutional water available will be less than that introduced to the tailings basin during the MN DNR/U of MN study. Consequently, EC levels may increase during this time period. However, as the pit

fills with tailings, the volume of water in the clear water pool, and therefore water available for recycling, decreases. In order to meet their process needs, Inland will have to supplement this flow with water from other sources. The make-up water required subsequent to year two of tailings deposition is predicted to exceed that during the MN DNR/U of MN study. As long as the source of the make-up water is dilute (e.g. the Enterprise or Sauntry Pits, which are already used as make-up water), EC levels in plant discharges will remain close to present levels. Therefore, plant discharge samples collected during the range-wide study represent the best available empirical estimate of the process water chemistry that will enter the Minorca Pit.

Since the Minorca Pit already contains water, it was necessary to calculate the change in water chemistry that results from mixing process water with that already present (i.e. the clear water pool) as well as ground water and precipitation inputs to the pit. Based on a preliminary tailings disposal plan (Indeco, 1999) and previous estimates of net precipitation and ground water flow (Normaco, 1997; Adams, 1998), two water balances were developed for the Minorca Pit clear water pool over the ten year tailings deposition plan. Changes in clear water pool chemistry were calculated assuming a well-mixed system and also a plug-flow system for both water balances. Thus four calculations provided a range of EC concentrations that can be expected in the clear water pool over the ten year operational time period. Since the clear water pool is anticipated to dominate ground water outflow from the Minorca Pit between deposition years five and eight, EC concentrations calculated for that time period represent the clear water pool source term.

#### 4.1.2. Tailings Pore Water Source Term

Water samples collected from a seep and two wells in the north dike of the tailings basin at Inland represented the closest operational simulation of tailings-water interaction expected in the Minorca Pit (Berndt and Lapakko, 1997a; Berndt et al., 1998, 1999). An additional water sample was collected from a seep in the interior dike late in the study (Berndt et al., 1999). Six operational field measurements of tailings pore water chemistry were also collected from the Snively Pit at US Steel-Minntac (Jakel and Lapakko, 1999a). The Snively Pit represents the only existing case of in-pit taconite tailings disposal in Minnesota. This situation provided data which will be used to represent the potential long-term impacts of in-pit taconite tailings disposal on ground water quality.

Tailings pore water quality was also measured in controlled field experiments. In-pit disposal of Laurentian taconite tailings was simulated using polyethylene tanks (d = 4 ft., h = 10 ft.) at the MN DNR field experimental facility in Hibbing, MN (Berndt and Lapakko, 1997a; Jakel et al., 1998; Jakel and Lapakko, 1999b). Two tanks were filled with tailings and process waters from Inland's operation and left open to the atmosphere. Tailings pore water samples were collected from wells set approximately four feet into the tailings. Sixteen tailings pore water samples were collected over 116 weeks.

Laboratory experiments consisted of tailings from Laurentian ore and process waters collected directly from the tailings discharge pipe at Inland and transferred into two plastic columns (d =

2 in., h = 15 ft.) fit with a sampling port at the base (Berndt and Lapakko, 1997a). The columns were secured in a vertical position and covered with an opaque plastic sheet to eliminate light. These columns simulated conditions that would be expected in the Minorca Pit as it is filled with tailings. Nine water samples were collected periodically over a period of seven months.

Once tailings and process waters have been deposited in a pit, it is likely that process waters will eventually be replaced by precipitation and possibly ground water. In order to simulate these two events, process water in one column was replaced with deionized water to simulate rain water and the other was injected with ground water obtained from local wells drilled into the Biwabik aquifer (Berndt et al., 1998). The resultant water chemistry data from these experiments were used as input for geochemical modeling. These calculations provided additional insight into the reactions controlling EC levels in tailings pore waters.

4.2. Transport in the Biwabik Aquifer

Field measurements of water samples collected from eleven different wells in the Biwabik formation aquifer were analyzed during this study (Berndt et al., 1998). These measurements represented the best estimate of background EC levels in the Biwabik aquifer.

In order to gain additional insight into chemical controls on EC levels in the Biwabik aquifer, geochemical calculations were computed using the Geochemist's Workbench version 2.0 (Bethke, 1994). This model provided a useful tool for performing fluid speciation, mineral reaction, and surface adsorption calculations (Berndt and Lapakko, 1997a, b; Berndt, 1998; Berndt et al., 1998, 1999).

4.3. Concentration Changes in the Missabe Mountain Pit

#### 4.3.1. Dilution

Dilution by non-impacted inputs to the Missabe Mountain Pit (e.g. precipitation and local ground waters), as well as the volume of water stored in the pit will decrease elevated EC levels entering the Missabe Mountain Pit from the Minorca Pit. The Missabe Mountain Pit receives approximately 1.12 billion gallons of water per year from precipitation and ground water (Wiskow, 1998). Of the 1.12 billion gallons of water entering the Missabe Mountain Pit each year, a temporary maximum input from the Minorca Pit of 0.441 billion gallons per year (39%; Adams, 1998) is expected for years five to ten after tailings deposition in the Minorca Pit begins. The remaining 0.679 billion gallons per year represents non-impacted precipitation and ground water from local sources. For the post-reclamation scenario, flow from the Minorca Pit to the Missabe Mountain Pit will decrease to approximately 0.237 billion gallons per year (21%; Adams, 1998), or lower depending on the type of vegetation established on the tailings surface. These interpretations are considered to be the worst case scenarios.

Using the preliminary tailings deposition plan for the Minorca Pit (Indeco, 1999) along with the estimated contributions of ground water from the Minorca Pit (Adams, 1998, 1999) and a generalized water balance for the Missabe Mountain Pit (HDR, 1997; Wiskow, 1998), a multi hypothetical approach was developed for determining the extent to which Minorca Pit outflow will be diluted in the Missabe Mountain Pit. This multi hypothetical approach took into consideration numerous variables including:

- 1. multiple source term magnitudes,
- 2. a shift from a clear pool to a tailings pore water source term at deposition year eight,
- 3. changes in ground water flow rates from the Minorca Pit over time based on the two reclamation conditions,
- 4. two different lengths of time to represent the "temporary maximum" ground water outflow from the Minorca Pit, and
- 5. two different interpretations of the Minorca Pit contribution to the flow-weighted average concentration of Missabe Mountain Pit inputs.

This approach resulted in twelve separate calculations of EC concentrations changes in the Missabe Mountain Pit due to continuous dilution over a fifty year time period. In order to simplify the presentation, only the worst case scenarios are presented graphically. However, a summary of all twelve calculations can be found in Appendix 3.

In addition to the variables considered above, this approach was based on three important assumptions, each of which is intended to provide the most conservative analysis. First, it assumes that 100 % of Minorca Pit outflow reports immediately to the Missabe Mountain Pit. As discussed in section 3.2, this assumption can neither be proved nor disproved.

Second, tailings deposition into the Minorca Pit is assumed to begin in 2004. This is approximately when Inland anticipates running out of room in their existing tailings basin. 2004 is also a convenient year because it implies that ground water outflow from the Minorca Pit would begin in 2009, the year that the water levels in the Missabe Mountain and Rouchleau Pits are expected to breach the earthen berm between them. At this time, the volume of the Missabe Mountain Pit below the berm has been calculated to be 5.6 billion gallons (Wiskow, 1998). Thus, 5.6 billion gallons can be used as the starting, dilutional, volume of water in the Missabe Mountain Pit just before inflow from the Minorca Pit arrives. It is important to remember that the years selected here may not correspond to the final disposal plan, and therefore, must be treated as a hypothetical situation rather than fact.

Third, despite the fact that the water elevation in the Missabe Mountain and Rouchleau Pits will breach the berm separating them at some point during Inland's disposal plan, it was assumed that there would be no mixing of water between the two pits. Thus, an initial pit volume of 5.6 billion gallons was used rather than the total combined volume of 8 billion gallons. This is not entirely realistic, however, it reduces the amount of dilutional water available within the Missabe

Mountain Pit. Consequently, it yields a conservative estimate of EC concentration changes due to inflow from the Minorca Pit.

#### 4.3.2. Geochemical Reactions

Water quality data were collected from operational sites as well as field and laboratory experiments, which simulated the reaction environment in the Missabe Mountain Pit. Operational surface water measurements were collected from the plant discharge to the tailings basin and from the reclaim barge where clarified water is recycled back to the plant (Berndt and Lapakko, 1997a, b; Berndt et al., 1998, 1999). Tailings basin surface water and Missabe Mountain Pit water are similar in that they both receive dilutional water from precipitation and surface runoff. Furthermore, both waters are exposed to the atmosphere, and therefore, have similar chemical environments. Thus, geochemical controls on EC levels in the tailings basin will likely represent those in the Missabe Mountain Pit. As an additional measure of confidence in these assumptions, water samples from five depths in the Missabe Mountain Pit were collected in March, 1999 (Lapakko and Jakel, 1999).

Chemical controls in surface waters associated with taconite tailings were also examined in field and laboratory experiments. The field tank experiments were designed such that approximately 4.5 feet of surface water stood above the taconite tailings, exposed to the atmosphere (Berndt and Lapakko, 1997a; Jakel et al., 1998; Jakel and Lapakko, 1999b). This situation simulated conditions in the tailings basin, and provided information regarding the persistence of EC's in these waters.

In order to better define the persistence of manganese in the Missabe Mountain Pit, batch experiments were conducted using waters obtained from monitoring well #6 at Inland and the Missabe Mountain Pit (Jakel et al., 1999c). Five separate dilutions were mixed in 2.5 gal buckets with a small hole punched in the lids to allow air transfer and stored at approximately 46 °F. These experiments were intended to simulate a situation where water with elevated EC levels mixed with water in the Missabe Mountain Pit. That is, they examined reactions in mixtures of water exiting a tailings impoundment under reducing conditions and water from the Missabe Mountain Pit.

#### 4.4. Chemical Analyses

Each water sample was analyzed for approximately 82 inorganic parameters including pH, alkalinity, temperature, and major and trace cations and anions. Temperature and pH (Beckman model 11 meter with Ross model 8165 combination electrode) were determined on site, while alkalinity titrations (APHA et al., 1995) were conducted at the MN DNR laboratory in Hibbing, MN. The levels of cations were analyzed by inductively coupled plasma mass spectrometry (ICP-MS, Perkin Elmer mode-SCIEX-Elan 5000) while anions were measured using ion chromatography (IC, Dionex Ion Chromatograph fitted with GP40 gradient pump, CD20 conductivity detector, and two AS4A anion exchange columns) at the U of MN.

#### 5. EC Summaries

Source terms, transport terms, and expected levels in the Missabe Mountain Pit for each of the four EC's are presented in the following discussion. These values are also compared to primary and secondary drinking water quality standards (Table 1). Finally, potential treatment issues for the Virginia Public Utility are considered

#### 5.1. Manganese

#### 5.1.1. Manganese Source Term

Manganese is released by dissolution of manganese-bearing minerals present in the tailings (Mattson, 1996). Based on the data collected during the range-wide study, a manganese source term range of 0.01 mg/L to 7 mg/L was selected for the Minorca Pit (Table 1). Manganese concentrations in oxygenated waters, which are representative of the **clear water pool** in the Minorca Pit, were at the lower end of this range. The oxygenated waters sampled include existing tailings basin surface waters, oxygenated waters in field tank and laboratory batch experiments, and water from abandoned open pits, including the Missabe Mountain Pit. These low levels are due to the unstable nature of dissolved manganese in oxygenated waters resulting in oxidation of manganese to  $MnO_2$ . Since water contained in the Minorca Pit through the clear water pool will be well oxygenated, manganese levels in the waters exiting the Minorca Pit through the clear water pool are expected to be approximately 0.01 mg/L.

Manganese levels in **tailings pore waters** during the range-wide study ranged from 0.05 mg/L to 7 mg/L. The 0.05 mg/L value was representative of manganese concentrations observed in waters associated with tailings from the Laurentian Pit (e.g. column and tank experiments). It is likely that the tailings that Inland has proposed to dispose of in the Minorca Pit will be compositionally similar to these tailings. However, the ore body composition may vary, and therefore, there is no guarantee that manganese concentrations will remain as low as 0.05 mg/L. The upper end of this range, 7 mg/L, was defined by the maximum manganese concentration observed in the wells on the north dike of Inland's tailings basin. This value may have been elevated by factors not anticipated to be influential in the Minorca Pit (e.g. incorporation of organic matter or other acid generating material with the tailings).

#### 5.1.2. Manganese Transport in the Biwabik Aquifer

The most conservative estimate of manganese levels in Minorca Pit ground water transported through the Biwabik aquifer assumes no dilution or removal due to chemical reactions. Based on this assumption, the manganese transport term will equal the source term from the Minorca Pit. That is, the manganese transport term will range from 0.01 mg/L to 7 mg/L.

Despite this conservative assumption, it is likely that ground water outflow from the Minorca Pit will be diluted by other ground water sources in the aquifer. The extent of this dilution

cannot be quantified. However, it was accounted for in the calculation of dilution in the Missabe Mountain Pit as the net dilution of Minorca Pit flow by water entering the Missabe Mountain Pit (i.e. the flow-weighted average input concentration to the Missabe Mountain Pit).

If Minorca Pit ground waters do mix with ground water already present in the aquifer, geochemical processes can be expected to control manganese levels during transport. The relatively high levels of alkalinity found in the aquifer suggested that manganese levels may be controlled by the solubility of a manganese carbonate phase (e.g. rhodochrosite). Geochemical calculations based on the observed water chemistry in an environment isolated from the atmosphere indicated that manganese levels could not exceed 1 mg/L in the Biwabik aquifer if these levels are controlled by rhodochrosite solubility (Lapakko and Jakel, 1999).

#### 5.1.3. Manganese in the Missabe Mountain Pit

In addition to water from the Minorca Pit, the Missabe Mountain Pit will receive input from precipitation and other ground water sources. It is estimated that Minorca Pit outflow will constitute a temporary maximum of 39 percent of this total input (Adams, 1998). At this temporary maximum, manganese levels in the Missabe Mountain Pit would be 1.7 mg/L based on dilution alone. This assumes that manganese levels in other input waters are similar to that of the Biwabik aquifer (It should be noted that manganese concentrations in precipitation will be lower than this level). This calculation further assumes that the water in the Rouchleau Pit does not provide dilution in the Missabe Mountain Pit. Thus, it is likely that manganese levels in the Missabe Mountain Pit will be less than 1.7 mg/L.

After the site has been reclaimed flow from the Minorca Pit to the Missabe Mountain Pit will decrease (Adams, 1998). This would increase dilution in the Missabe Mountain Pit, and manganese concentrations could potentially be reduced to less than 1.6 mg/L once forest vegetation becomes established.

In addition to dilution, manganese concentrations in the Missabe Mountain Pit will be reduced by oxidation and subsequent precipitation of manganese oxyhydroxide, which occurs commonly in oxygenated natural waters (Stumm and Morgan, 1981; Langmuir, 1997). Oxidation is the mechanism responsible for maintaining the low manganese concentrations in large abandoned open pits across the range reported by Pierce and Tomcko (1989) and in surface waters associated with taconite tailings (Berndt et al., 1999; Jakel et al., 1998; Jakel and Lapakko, 1999b). Operational measurements and field and laboratory experiments indicate that manganese levels are unlikely to exceed 0.01 mg/L in oxygenated waters associated with taconite tailings (Figure 3; Berndt et al., 1999; Jakel et al., 1998; Jakel and Lapakko, 1999b,c; Pierce and Tomcko, 1989).

The presence of oxygenated water in the Missabe Mountain Pit was reported in previous work (MDH, 1998) and verified by measurements in this study (Lapakko and Jakel, 1999). Under these conditions, thermodynamics predict equilibrium manganese concentrations of at least three

orders of magnitude below those measured during this study. Oxidation of manganese and precipitation of manganese oxyhydroxide was verified as operative in a laboratory experiment conducted in the course of this study (Jakel and Lapakko, 1999c). The experiment was conducted using a mixture of water exiting a tailings impoundment under reducing conditions and water from the Missabe Mountain Pit. For mixtures with initial manganese concentrations less than 2 mg/L, manganese concentrations decreased to less than 0.01 mg/L within fourteen weeks. The retention time for water in the Missabe Mountain Pit is approximately twenty two times longer than the time required for this reaction to occur. Therefore, oxidation is expected to control manganese levels within the Missabe Mountain Pit below the secondary standard.

#### 5.1.4. Comparison to Water Quality Standards

Manganese concentrations will meet the health-based water quality standard determined for this project (1.3 mg/L; MDH, 1998) as well as primary (0.1 mg/L) and secondary (0.05 mg/L) drinking water quality standards at the Virginia water supply intake (Figure 3). This conclusion was reached using the maximum manganese source concentration (7 mg/L), assuming no removal in the Biwabik aquifer, using the minimum projected dilution and chemical reactions within the Missabe Mountain Pit. Thus, manganese concentrations in the Missabe Mountain Pit will decrease to meet these standards largely as a result of chemical reaction.

Several factors which may further mitigate manganese concentrations at the Virginia water supply intake were ignored in the analysis presented above. First, the source concentration may be considerably lower than the 7 mg/L value used, as low as 0.05 mg/L based on field experiments. Furthermore, manganese levels in the Snively Pit tailings averaged 1.3 mg/L, indicating that long-term manganese concentrations will not increase over time. Second, it is not unlikely that manganese concentrations will decrease during flow through the Biwabik aquifer due to dilution and/or chemical reaction. Third, dilution will likely reduce manganese concentrations to lower levels in the Missabe Mountain Pit.

#### 5.1.5. Treatment Issues for the Public Utility

The Virginia Public Utility currently relies on sedimentation basins and pressure sand filters to remove particulate matter from their water supply (Wiskow, 1998). However, they are testing a membrane filtration system on a pilot-scale for possible future use. They are also considering a gravity filtration system. These systems are expected to be able to remove manganese as long as the input concentration is below 0.05 mg/L, the secondary water quality standard. Manganese concentrations in the Missabe Mountain Pit presently meet water quality standards, and it is predicted that these standards will be met if tailings are disposed in the Minorca Pit. Consequently, no treatment issues are anticipated.

#### 5.2. Fluoride

#### 5.2.1. Fluoride Source Term

Fluoride is released from soluble fluoride phases produced as a result of the induration and scrubbing processes during taconite processing (Berndt and Lapakko, 1997a; Berndt et al., 1998, 1999; Jakel and Lapakko, 1999d). Based on the data collected during the range-wide study, a fluoride source term range of 1 to 6 mg/L was selected (Table 1). Analyses of plant discharges and calculation of dilution in the Minorca Pit clear water pool led to a **clear water pool source term** of 6 mg/L. Since fluoride is released during taconite processing, fluoride levels in plant discharges may increase if plant process waters are not supplemented with make-up water from dilute sources (e.g. Sauntry and Enterprise Pits). However, the preliminary tailings disposal plan (Indeco, 1999) indicates that substantial amounts of make-up water will be required after the first two years of tailings deposition in the Minorca Pit.

Fluoride levels in **pore waters** associated with Inland's tailings during the range-wide study ranged from 1 mg/L to 6 mg/L. Unlike the other three ECs, the range of fluoride concentrations in tailings pore waters appeared to be normally distributed. Therefore, it is appropriate to use an average concentration as a refined source term. Based on sixty two tailings pore water samples collected from field and laboratory experiments, as well as measurements taken at Inland's tailings basin, the average fluoride concentration in tailings pore waters was 3.2 mg/L with a standard deviation of 1.2. This value represents the most likely tailings pore water source term for fluoride in the Minorca Pit. The upper end of the range of observed fluoride concentrations (6 mg/L) was typical of tailings pore analyses from field tank experiments. This value will be considered the worst case scenario in this assessment.

#### 5.2.2. Fluoride Transport in the Biwabik Aquifer

The most conservative estimate of fluoride levels in Minorca Pit ground water transported through the Biwabik aquifer assumes no dilution or removal due to chemical reactions. Based on this assumption, the fluoride transport term will range from 1 mg/L to 6 mg/L. Despite this conservative assumption, it is likely that ground water outflow from the Minorca Pit will be diluted by other ground water sources in the aquifer. The extent of this dilution cannot be quantified. However, it was accounted for in the calculation of dilution in the Missabe Mountain Pit as the net dilution of Minorca Pit flow by water entering the Missabe Mountain Pit (i.e. the flow-weighted average input concentration to the Missabe Mountain Pit).

If Minorca Pit ground waters do mix with ground water already present in the aquifer, geochemical processes can be expected to control fluoride levels during transport. Fluoride levels would be expected to remain below the fluorite solubility limit. Using the solubility constant determined by Berndt et al. (1999) and calcium levels in the Biwabik aquifer (33 to 70 mg/L; Berndt et al., 1998), the fluoride concentrations in the aquifer could be in the range of 4.3 to 6.2 mg/L.



#### 5.2.3. Fluoride in the Missabe Mountain Pit

Within the Missabe Mountain Pit fluoride concentrations will be diluted by surficial and local ground water inputs to the pit. At the temporary maximum input of 39 percent from the Minorca Pit, the maximum calculated fluoride concentration in the Missabe Mountain Pit will be 1.6 mg/L (Figure 4) assuming a fluoride concentration in other ground water inputs is similar to that of the Biwabik aquifer (i.e. approximately 0.28 mg/L; Berndt et al., 1998). It should be noted, however, that fluoride concentrations in precipitation will be lower than this level. This calculation further assumes that the water in the Rouchleau Pit does not provide dilution in the Missabe Mountain Pit. Thus, it is likely that fluoride levels in the Missabe Mountain Pit will be less than 1.6 mg/L. After the Minorca Pit has been reclaimed, dilution in the Missabe Mountain Pit will result in fluoride levels lower than 1.5 mg/L.

Once the water exiting the Minorca Pit is dominated by tailings pore water, fluoride concentrations in flow from the Minorca Pit will decrease. Based on the more refined source term for this period, 3 mg/L, yielding a maximum fluoride concentration of 0.9 mg/L in the Missabe Mountain Pit. Once final reclamation is in place flow from the Minorca Pit will decrease and, consequently, so will average concentrations for the water input to the Missabe Mountain Pit.

#### 5.2.4. Comparison to Drinking Water Quality Standards

At maximum ground water input from the Minorca Pit, fluoride levels in the Missabe Mountain Pit are expected to be lower than both the primary and secondary drinking water standards of 4 and 2 mg/L, respectively. Using fluoride concentrations of 6 mg/L for the source term and 0.28 mg/L for other inputs to the Missabe Mountain Pit yields a maximum fluoride concentration of 1.6 mg/L (Figure 4).

#### 5.2.5. Treatment Methods Used at the Virginia Public Utility

Currently, the Virginia Public Utility fluoridates the water supply for the city of Virginia (Wiskow, 1998). Fluoride levels in water entering the public utility are monitored an a monthly basis. If fluoride levels were to increase in the Missabe Mountain Pit due to disposal of taconite tailings in the Minorca Pit, additional fluoride in the water supply may not be necessary. If fluoride levels in the Missabe Mountain Pit were to increase rapidly, water entering the utility may require more frequent monitoring intervals.

#### 5.3. Molybdenum

#### 5.3.1. Molybdenum Source Term

The only potential mechanisms of molybdenum release that have been identified at present are the breakdown of lubricants containing  $MoS_2$  and corrosion of grinding media used during taconite processing. Based on the data collected during the MN DNR/U of MN study, a molybdenum source term range of 1 to 130 ug/L was selected (Table 1). The upper end of this range was calculated based on dilution of process water discharged from the plant in the Minorca Pit clear water pool. This represents a short-term, **clear water pool source term** that is appropriate to use between the fifth and eighth years of operation at the Minorca Pit.

Molybdenum levels in **tailings pore waters** during the range-wide study ranged from 1 ug/L to 45 mg/L. The upper end of this range represented analyses of tailings pore waters from the field and laboratory experiments (i.e. process water columns). The lower end of this range was defined by tailings pore waters from wells and seeps around Inland's tailings basin. Since the molybdenum release is the result of operational processes, the source term is expected to decrease to extremely low levels (as seen in the Snively Pit) after site closure.

#### 5.3.2. Molybdenum Transport

The most conservative estimate of molybdenum levels in Minorca Pit ground water transported through the Biwabik aquifer assumes no dilution or removal due to chemical reactions. Based on this assumption, the molybdenum transport term will range from 1 ug/L to 130 ug/L. Despite this conservative assumption, it is likely that ground water outflow from the Minorca Pit will be diluted by other ground water sources in the aquifer. The extent of this dilution cannot be quantified. However, it was accounted for in the calculation of dilution in the Missabe Mountain Pit as the net dilution of Minorca Pit flow by water entering the Missabe Mountain Pit (i.e. the flow-weighted average input concentration to the Missabe Mountain Pit).

If Minorca Pit ground waters do mix with ground water already present in the aquifer, geochemical processes can be expected to control molybdenum concentrations during transport. Geochemical calculations indicated that molybdenum may be attenuated by iron oxides in the aquifer depending on the pH of water in the aquifer. Based on measurements from wells in the Biwabik formation, the pH of these waters ranges from 6.7 to 8.1. In this pH range, molybdenum levels in the aquifer are expected to decrease during transport through the aquifer, although the extent to which this will occur cannot be quantified. In general, molybdenum adsorption to iron oxides is most likely to occur during the period of maximum flow from the Minorca Pit (e.g. prior to reclamation of the site). This is also the time period in which dilution will have the least impact on molybdenum levels in the Missabe Mountain Pit.

#### 5.3.3. Molybdenum in the Missabe Mountain Pit

Molybdenum concentrations from the Minorca Pit to the Missabe Mountain Pit will be diluted by inputs from other sources. At the temporary inflow maximum, the maximum molybdenum concentrations in the Missabe Mountain Pit may be as high as 25 ug/L (Figure 5), assuming molybdenum concentrations in inputs other than that from the Minorca Pit are similar to those of the Biwabik aquifer (e.g. approximately 0.24 ug/L; Berndt et al., 1998). It should be noted, however, that molybdenum concentrations in precipitation will be lower than this level. This calculation further assumes that the water in the Rouchleau Pit does not provide dilution in the Missabe Mountain Pit. Thus, it is likely that molybdenum levels in the Missabe Mountain Pit will be less than 25 ug/L.

The maximum molybdenum level in the Missabe Mountain Pit is reached during the time period when the clear water pool dominates outflow from the Minorca Pit (i.e. clear water pool source term = 130 ug/L). As the pit continues to fill with tailings, the source term will become dominated by tailings pore waters, reducing the source term to 45 ug/L. Consequently, molybdenum concentrations in the Missabe Mountain Pit will decrease to less than 22 ug/L. No chemical controls are expected to influence molybdenum levels in the Missabe Mountain Pit.

#### 5.3.4. Comparison to Water Quality Standards

Even at maximum ground water input from the Minorca Pit, molybdenum levels in the Missabe Mountain Pit are expected to be lower than the primary drinking water standard of 30 ug/L (Figure 5). Consequently, no treatment issues at the Virginia Public Utility are expected to arise.

#### 5.4. Arsenic

5.4.1. Arsenic Source Term

Arsenic is believed to be released by the oxidation of trace amounts of pyrite present in the tailings. Based on analyses of Inland's plant discharges and tailings pore waters an arsenic source term range of 0.1 to 7 ug/L was selected (Table 1). The lowest arsenic levels were found in the north seep at Inland. These values are actually lower than those measured in the Biwabik aquifer (Berndt et al., 1998) and the Missabe Mountain Pit (Lapakko and Jakel, 1999). The upper end of this range was defined by a calculated value for the **clear water pool** and a few high values observed in the wells at Inland and the "rain water" column experiments. Despite this wide range of values, the majority of **tailings pore waters** sampled during this study contained 2 - 4 ug/L arsenic.

#### 5.4.2. Arsenic Transport

The most conservative estimate of arsenic levels in Minorca Pit ground water transported through the Biwabik aquifer assumes no dilution or removal due to chemical reactions. Based on this assumption, the arsenic transport term will range from 0.1 ug/L to 7 ug/L.

Despite this conservative assumption, it is likely that ground water outflow from the Minorca Pit will be diluted by other ground water sources in the aquifer. The extent of this dilution cannot be quantified. However, it was accounted for in the calculation of dilution in the Missabe Mountain Pit as the net dilution of Minorca Pit flow by water entering the Missabe Mountain Pit (i.e. the flow-weighted average input concentration to the Missabe Mountain Pit).

If Minorca Pit ground waters do mix with ground water already present in the aquifer, geochemical processes can be expected to control arsenic levels during transport. Geochemical calculations indicated that arsenic will be attenuated by iron oxides in the aquifer 2 to 13 times longer than nonreactive elements chloride and bromide. Arsenic levels in the aquifer are expected to decrease during transport through the aquifer, although the extent to which this will occur cannot be quantified. In general, arsenic adsorption to iron oxides is most likely to occur during the period of maximum flow from the Minorca Pit (e.g. prior to reclamation of the site). This is also the time period in which dilution will have the least impact on arsenic levels in the Missabe Mountain Pit.

#### 5.4.3. Arsenic in the Missabe Mountain Pit

Arsenic levels in the Missabe Mountain Pit are expected to be 2.2 ug/L at the temporary inflow maximum from the Minorca Pit (Figure 6), assuming concentrations in the dilutional water similar to those of the Biwabik aquifer (e.g. approximately 0.5 ug/L; Berndt et al., 1998). It should be noted, however, that arsenic concentrations in precipitation will be lower than this level. This calculation further assumes that the water in the Rouchleau Pit does not provide dilution in the Missabe Mountain Pit. Thus, it is likely that arsenic levels in the Missabe Mountain Pit will be less than 2.2 ug/L. After the site has been reclaimed, flow from the Minorca Pit to the Missabe Mountain Pit will decrease (Adams, 1998) and arsenic concentrations in the Missabe Mountain Pit will decrease to less than 2 ug/L.

Arsenic levels in the Missabe Mountain Pit may also be reduced by chemical and/or biological oxidation and subsequent precipitation of iron oxides. Geochemical calculations indicate that arsenic will tend to co-precipitate with iron oxides (Berndt, 1998), further reducing arsenic levels in the Missabe Mountain Pit.

#### 5.4.4. Comparison to Water Quality Standards

Even at maximum ground water input from the Minorca Pit, arsenic levels in the Missabe Mountain Pit are expected to be considerably lower than the primary drinking water standard of 50 ug/L (Figure 6). However, the US EPA is expected to lower this standard by the year 2001. Arsenic levels in the Missabe Mountain Pit are anticipated to meet the future drinking water quality standard if it is reduced to the range of 5 - 10 ug/L. Therefore, no treatment issues at the Virginia Public Utility are expected to arise.

#### 6. Conclusions

#### 6.1. Worst Case Scenario

Outflow from the Minorca Pit will have EC levels which are elevated relative to those presently in the Missabe Mountain Pit and Biwabik aquifer. Minorca Pit flow which enters the Missabe Mountain Pit will elevate EC levels in the Missabe Mountain Pit above those presently observed. However, based on evaluation of the worst case scenario, dilution and geochemical controls are expected to maintain EC levels in the Missabe Mountain Pit below existing health-based and drinking water quality standards.

Manganese levels in Missabe Mountain Pit input waters are expected to meet the health-based standard set by the MDH (1998) and the secondary drinking water quality standard due to chemical reactions in the pit. Oxidizing conditions in the Missabe Mountain Pit are expected to promote manganese removal which will reduce manganese concentrations to levels presently found in the pit.

Fluoride and molybdenum levels are not expected to exceed the drinking water quality standards in the Missabe Mountain Pit. No geochemical controls are expected to reduce these levels during transport in the Biwabik aquifer. However, dilution of Minorca Pit inputs to the Missabe Mountain Pit is expected to be sufficient to reduce fluoride and molybdenum concentrations to levels lower than the drinking water quality standards but higher than those presently found in the Missabe Mountain Pit.

Dilution is also expected to maintain arsenic concentrations in the Missabe Mountain Pit to levels lower than the drinking water quality standards but higher than those presently found in the Missabe Mountain Pit. Arsenic concentrations in the Missabe Mountain Pit may be reduced further by co-precipitating with iron oxyhydroxides.

#### 6.2. Mitigating Factors to the Worst Case Scenario

The above assessment was based on the worst case scenarios for each EC. However, several mitigating factors exist that would tend to decrease EC levels actually observed in the Missabe Mountain Pit:

1. Clear water pool source terms were determined assuming the maximum EC levels measured in plant discharges to the tailings basin during the MN DNR/U of MN study.

However, discharge concentrations may decrease after several years of tailings deposition in the Minorca Pit because process waters needs will have to be met with make-up water from other sources (presumable the Sauntry or Enterprise Pits). This is a particularly important consideration in assessing fluoride and molybdenum concentrations in the clear water pool.

- 2. During the time period when the clear water pool dominates outflow from the Minorca Pit (years 5 8), our calculations assumed that the clear water pool represented 100% of the outflow. It is more likely that ground water outflow during that time period will be a mixture of water from the clear water pool and tailings pore waters. This will tend to decrease the magnitude of the molybdenum source term (130 ug/L in the clear water pool, 45 ug/L in tailings pore waters). However, it would tend to increase the manganese source term (<0.01 mg/L in the clear water pool, 7 mg/L in tailings pore waters).
- 3. The manganese tailings pore water source term (7 mg/L) was based on the maximum measured concentration in wells along the existing tailings basin. In the absence of acid generating materials (e.g. organic matter) in the tailings mass, manganese concentrations in tailings pore waters are likely to be less than 1 mg/L.
- 4. Minorca Pit ground waters were assumed to flow through the Biwabik aquifer to the Missabe Mountain Pit with no interaction with existing ground water or host rock. However, it is likely that manganese, molybdenum, and arsenic will be attenuated to some degree in the aquifer. Based on geochemical calculations, manganese levels in the aquifer are unlikely to exceed 1 mg/L. Molybdenum and arsenic attenuation could not be quantified, but will decrease due to adsorption to iron oxides present in the host rock.
- 5. A value of 39% was used to represent the Minorca Pit contribution to the flow-weighted average EC concentrations in the net inputs to the Missabe Mountain Pit. This value was decreased to 28% after additional interpretation (Adams, 1999), which would decrease the impact that outflow from the Minorca Pit would have on water quality in the Missabe Mountain Pit.
- 6. Dilution within the Missabe Mountain Pit did not include the volume of water in the Rouchleau Pit nor precipitation and ground water inputs to that pit. Depending on the timing of tailings disposal in the Minorca Pit, it is likely that the water level in these two pits will have risen above the berm currently separating them. Therefore, the volume of dilutional water available will be larger than that used to assess the worst case scenario.
- 7. The water balance used to calculate flow-weighted average EC concentrations did not distinguish between precipitation and ground water. Therefore, it was assumed that all inputs, other than flow from the Minorca Pit, had EC levels similar to those measured in the Biwabik aquifer. This assumption overestimates EC levels in the net inputs to the Missabe Mountain Pit, since precipitation does not contain ECs.

#### 6.3. Recommendations

- 1. Water quality of plant discharges into the Minorca Pit should be monitored. If EC levels in these waters become elevated, Inland will need to make adjustments to maintain concentrations in the Minorca Pit at acceptable levels. This may be particularly important for molybdenum in the clear water pool. Whereas rigorous analysis of acceptable discharge levels has not been conducted, the values used in this study resulted in Missabe Mountain Pit concentrations which met drinking water quality standards. Therefore, they represent one option for acceptable plant discharge levels.
- 2. Tailings pore water quality in the Minorca Pit should be monitored in order to insure accuracy of the predicted source terms. Conditions in the Minorca Pit may not be fully represented by those encountered in Inland's tailings basin or controlled experiments. Natural mineralogical variations in tailings composition or unforeseen changes in taconite processing methods could result in elevated levels of the four EC's or other elements in the Minorca Pit. Variables such as these could not be accounted for in this analysis.
- 3. Conditions in the Missabe Mountain Pit should be monitored to ensure that oxidizing conditions are maintained as the water level in this pit rises. If pit waters become reducing, manganese removal by natural processes may be compromised.
- 4. Monitoring of incoming water to the water treatment plant should continue and may require an increased sampling frequency. This will be particularly important for fluoride, since fluoridation adjustments will be necessary if fluoride levels in the Missabe Mountain Pit increase.

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Figure 1. The Missabe Mountain Pit is located approximately one half mile south of the Minorca Pit. This map designates a complex of interconnected pits (including the Columbia, Commodore, Missabe Mountain, Shaw-Moose, and Rouchleau) as the Missabe Mountain Pit.

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In order to evaluate potential impacts on water quality in the Missabe Mountain Pit, a direct connection with the Minorca Pit was assumed. EC concentrations were evaluated at four points along this flow path; 1) water exiting the Minorca Pit, 2) transport through the aquifer, 3) flow-weighted average concentrations of inputs to the Missabe Mountain Pit, and 4) dilution and chemical reactions within the Missabe Mountain Pit.

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## Manganese Levels Observed in Oxygenated Environments



Figure 3. Manganese levels in the Missabe Mountain Pit are expected to be less than 0.01 mg/L (dashed line). Low levels of dissolved manganese are observed in surface waters associated with taconite tailings and in mine pits in northern Minnesota due to chemical oxidation of dissolved manganese, and subsequent precipitation of solid manganese oxide, MnO<sub>2</sub>. A few elevated manganese levels were observed in tailings basins during extended periods of ice cover (e.g. winter).

Predicted Fluoride Levels in the Missabe Mountain Pit Due to Elevated Input Levels from the Minorca Pit



## Range of Estimates

- Minimum
- × Refined Estimate
- Maximum
- Figure 4. Although no geochemical controls are expected for fluoride in the Missabe Mountain Pit, dilution by the volume of water stored within the pit will be sufficient to reduce fluoride levels below the primary and secondary drinking water quality standards (4 mg/L and 2 mg/L, respectively).



Predicted Molybdenum Levels in the Missabe Mountain Pit Due to Elevated Input Levels from the Minorca Pit

Range of Estimates

- Minimum
- × Refined Estimate
- Maximum
- Figure 5. Although no geochemical controls are expected for molybdenum in the Missabe Mountain Pit, dilution by the volume of water stored within the pit will be sufficient to reduce fluoride levels below the drinking water quality standard (30 ug/L).



Predicted Arsenic Levels in the Missabe Mountain Pit Due to Elevated Input Levels from the Minorca Pit

## Range of Estimates

- Minimum
- × Refined Estimate
- Maximum
- Figure 6. Even at maximum input from the Minorca Pit, arsenic levels in the Missabe Mountain Pit are expected to be well below the current drinking water quality standard of 50 ug/L.

Terms	Conditions	Criteria	Mn (mg/L)	F (mg/L)	Мо	As
Minorca Pit Source Term <sup>1,2</sup>	Clear Water Pool	Clear Water Pool Deposition Year 5-8		6	130	4.5
	Tailings Pore Water	Deposition Year 8+	0.05 - 7	1 - 6	1 - 45 <sup>3</sup>	0.1 - 7
Biwabik Aquifer Transport	No Removal or		0.05 - 7	1 - 6	1 - 130	0.1 - 7
Term	Chemical Controls		14	4-6 <sup>5</sup>	na	36
	Dilution <sup>7,8</sup>	Temporary Maximum	0.02 - 1.7	0.3 - 1.6	1.4 - 25	0.5 - 2.1
Missaba Mountain Bit		Reclamation w/ Grasses	0.1 - 1.7	0.4 - 1.6	3.4 - 25	0.4 - 2.1
Wissabe Wouldain I it		Reclamation w/ forest	0.2 - 1.6	0.4 - 1.5	3.0 - 11	0.4 - 1.9
	Chemical Controls		< 0.019	na	na	na
		Health-based value	1.310	na	na	na
Drinking Water Quality Standards		Primary	0.1	4	30	50
		Secondary	0.0511	212	na	<1013

Table 1.Summary of the source terms, transport terms, expected levels in the Missabe Mountain Pit, and drinking water quality<br/>standards for the five EC's.

<sup>1</sup> A monitoring well should be installed in the Minorca Pit tailings in order to monitor fluctuations in the levels of the five EC's over time.

<sup>2</sup> Source terms for F and Mo will likely decrease over time, particularly after successful reclamation of the Minorca Pit.

<sup>3</sup> Mo source terms appeared to be dependent on the levels found in plant discharges, which may vary over time.

<sup>4</sup> Assumes chemical control by rhodochrosite solubility in the aquifer, calculation in Figure A2.1.

<sup>5</sup> Assumes chemical control by fluorite solubility (Berndt et al., 1999) in the aquifer based on measured calcium concentrations.

<sup>6</sup> This value was based on visual inspection of the distribution of arsenic levels in tailings pore waters during this study. It is intended to illustrate arsenic removal due to adsorption to iron oxides in the formation.

<sup>7</sup> These values were calculated assuming a dilution water composition based on that observed in the Biwabik aquifer wells (Berndt et al., 1998).

<sup>8</sup> Dilution factors of 6% - 21% depend upon implementation of successful reclamation at the Minorca Pit upon closure.

<sup>9</sup> This value assumes oxidizing conditions in the Missabe Mountain Pit will promote precipitation of manganese oxides. Based on measurements in the tailings basin and manganese oxidation experiments.

<sup>10</sup> This is a site-specific, health-based standard developed by the Minnesota Department of Health (1998).

<sup>11</sup> This is an aesthetic standard that the Virginia Public Utility must meet for the city water supply.

<sup>12</sup> The secondary fluoride standard is not an enforceable standard.

<sup>13</sup> The US EPA is considering lowering the primary arsenic standard to less than 10 ug/L in the future.

"na" = not applicable

## APPENDIX 1

#### SOURCE TERM DETERMINATIONS

- Table A1.1.
   Estimation of EC concentrations in the Minorca Pit clear water pool.
- Table A1.2.Summary of manganese source terms.
- Table A1.3.Summary of fluoride source terms.
- Table A1.4.Summary of molybdenum source terms.
- Table A1.5.Summary of arsenic source terms.

ELEMENT OF	DISCHARGE	ASSUMED	SOURCE OF	CONCENTRATION
CONCERN	CONC.	SYSTEM	HYDROLOGIC DATA	AT YEAR 10
Mn (mg/L)	0.1	well-mixed	Indeco, 1999	0.08
			Adams, 1998	0.07
		plug flow	Indeco, 1999	0.08
			Adams, 1998	0.07
F (mg/L)	7.6	well-mixed	Indeco, 1999	6.2
			Adams, 1998	5.6
		plug flow	Indeco, 1999	6.2
			Adams, 1998	5.6
Mo (ug/L)	160	well-mixed	Indeco, 1999	130
			Adams, 1998	119
		plug flow	Indeco, 1999	130
			Adams, 1998	119
As (ug/L)	5.5	well-mixed	Indeco, 1999	4.5
			Adams, 1998	4.1
		plug flow	Indeco, 1999	4.5
			Adams, 1998	4.1

 Table A1.1.
 Estimation of EC concentrations in the Minorca Pit clear water pool.

# Table A1.2.Summary of manganese source terms based on operational, field, and laboratory<br/>water chemistry measurements.

Clear Water Pool	:
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Data Source	Ν	Average Mn (mg/L)	Range (mg/L)
Tailings basin	11	0.01	0.001 - 0.076
Tank experiments	20	0.004	0.001 - 0.021
Mn oxidation experiments	4	0.002	0.004 - 0.009
Pierce and Tomcko, 1989	8	na	<0.01 - 22.5
Recommended Clear Pool Source Term			< 0.01

Tailings Pore Water:

Data Source	N	Average Mn (mg/L)	Range (mg/L)
Tailings discharge pipe	10	0.06	0.05 - 0.09
North seep at Inland	7	3.2	1.7 - 4.1
North wells at Inland	15	4.6	1.2 - 7.2
Snively Pit (USX)	6	1.3	1.0 - 1.9
Tank experiments	32	0.08	0.05 - 0.12
Process water columns	6	$0.6^{1}$	0.45 - 0.70
Rain water columns	6	0.3	0.26 - 0.34
Ground water columns	5	$0.2^{2}$	0.16 - 0.21
Recommended Pore Water Source Term			0.05 - 7

na = not applicable

<sup>1</sup> Mn levels appeared to be increasing at the end of the experiment, therefore the average from the last three data points of both columns was used here.

<sup>2</sup> Represents an average of the last five samples (weeks 12 to 30), when Mn levels stabilized.

 Table A1.3.
 Summary of fluoride source terms based on operational, field, and laboratory water chemistry measurements.

Data Source	N	Average F	Range
	IN	(mg/L)	(mg/L)
Tailings discharge pipe	10	4.6	2.3 - 7.6 <sup>1</sup>
North seep at Inland	8	2.3	1.2 - 3.0
North wells at Inland	15	2.5	0.6 - 3.6
Snively Pit (USX)	6	0.2	0.16 - 0.31
Tank experiments	22	$4.7^{2}$	3.6 - 5.9
Process water columns	6	3.0 <sup>3</sup>	2.8 - 3.0
Rain water columns	6	3.2	1.7 - 4.1
Ground water columns	3	$2.2^{4}$	2.1 - 2.3
Recommended Source Term			1 - 6 <sup>1</sup>

na = not applicable

<sup>1</sup> Clear water pool contribution expected to be no more than 6 mg/L.

<sup>2</sup> Fluoride levels stabilized after the first sixteen weeks of the experiment.

<sup>3</sup> Fluoride levels appeared to be decreasing at the end of the experiment, therefore, the average of the last three samples from both columns was used here. <sup>4</sup> Fluoride levels appeared to be increasing at the end of the experiment, therefore, . the average of the last three samples (weeks 20, 25, and 30) was used here.

Table A1.4.Summary of molybdenum source terms based on operational, field, and<br/>laboratory water chemistry measurements.

Data Source	N	Average Mo (ug/L)	Range (ug/L)
Tailings discharge pipe	10	110	68 - 157 <sup>1</sup>
North seep at Inland	8	7.1	1.5 - 13.7
North wells at Inland	15	6.4	3.0 - 8.4
Snively Pit (USX)	6	0.6	0.1 - 1.5
Tank experiments	32	24	13 - 45
Process water columns	6	24 <sup>2</sup>	15 - 34
Rain water column	6	11 <sup>3</sup>	7.1 - 19
Ground water column	3	9.44	8.7 - 9.9
Recommended Source Term		·	1 - 130 <sup>1</sup>

na = not applicable

.

<sup>1</sup> Clear water pool contribution expected to be no more than 130 ug/L.

 $^{2}$  Mo levels decreased throughout the experiment, therefore, the average of the last three samples from the two columns were used here.

<sup>3</sup> Mo concentrations appeared to be increasing at the end of the experiment, however, all six values were used.

<sup>4</sup> Mo concentrations appeared to be increasing at the end of the experiment, therefore, an average of the last three samples (weeks 20, 25, and 30) was used here.

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Table A1.5.	Summary of arsenic source terms based on operational, field, and laboratory
·	water chemistry measurements.

Data Source	N	Average As (ug/L)	Range (ug/L)
Tailings discharge pipe	10	3.6	1.9 - 5.5
North seep at Inland	8	1.1	0.2 - 2.1
North wells at Inland	15	4.1	1.5 - 8.1
Snively Pit (USX)	6	1.2	0.1 - 4.8
Tank experiments	32	2.4	0.6 - 4.2
Process water columns	10	$3.7^{1}$	2.1 - 5.4
Rain water columns	6	4.9	2.6 - 7.2
Ground water columns	8	2.5	1.2 - 3.7
Recommended Source Term	na		0.1 - 7

na = not applicable <sup>1</sup> Arsenic concentrations stabilized after six to ten weeks.

### APPENDIX 2

## TRANSPORT IN THE BIWABIK AQUIFER

Figure A2.1. Rhodochrosite solubility control on manganese levels in the Biwabik aquifer.

Figure A2.2. Fluorite solubility control on fluoride levels in the Biwabik aquifer.

Figure A2.3. Adsorption model depicting behavior of fluoride, molybdenum, and arsenic in the presence of iron oxide minerals.



Figure A2.1. Manganese levels in Biwabik Formation aquifer waters are believed to be controlled by the solubility of the mineral rhodochrosite ( $MnCO_3$ ). Within the range of pCO<sub>2</sub> (dashed vertical lines) and alkalinity (color lines) found in the Biwabik aquifer, manganese levels should not exceed 1 mg/L.



## Fluorite Solubility Control on Fluoride Levels

Figure A2.2. Maximum fluoride levels in the Biwabik Formation aquifer are likely to be controlled by the solubility of the mineral fluorite ( $CaF_2$ ; Berndt et al., 1999). Within the range of observed calcium concentrations in the Biwabik aquifer (vertical dashed lines), maximum fluoride levels are expected to range from 4.3 to 6.2 mg/L.



Figure A2.3. Geochemical adsorption model depicting behavior of adsorbing species in average tailings basin water reacting with minnesotaite, siderite, cristobalite, rhodochrosite, and 60 m<sup>2</sup> of hematite per liter of solution (Berndt, 1998). The reduction in pH leads to adsorption of arsenic and molybdenum.

## APPENDIX 3

## PREDICTION OF EC LEVELS IN THE MISSABE MOUNTAIN PIT

Table A3.1.	Summary of approaches used to estimate maximum impact on manganese levels in the Missabe Mountain Pit.
Table A3.2.	Summary of approaches used to estimate maximum impact on fluoride levels
	in the Missabe Mountain Pit.
Table A3.3.	Summary of approaches used to estimate maximum impact on molybdenum
	levels in the Missabe Mountain Pit.
Table A3.4.	Summary of approaches used to estimate maximum impact on arsenic levels
	in the Missabe Mountain Pit.
Table A3.5.	Summary of manganese oxidation information and data.

Table A3.1.	Summary of approaches used to estimate maximum impact on manganese
	levels in the Missabe Mountain Pit. Concentrations in mg/L.

	NO OUTFLOW FROM MINORCA PIT						
0	perations within the Mino	rca Pit	Missabe Mt Pit Concentration Estimates (mg/L)				
Depositional	Period of Max. Outflow	Reclamation	Minorca	Minorca Contribution to		Max. Estimated Conc. in	
Time Period	from Minorca	Conditions	Source Term	Missabe Net Input	Max. Net Input Conc.	Missabe During This	
(Years)	(deposition year)	·····			0.000 // 1	Time Period	
0-4	5-10	none	7	0%	0.003 (background)	0.0	
0-4	5-10	none		0%	0.0	0.0	
0-4	5.10	none	1	0%	0.0	0.0	
0-4	5.10	none	0.05	0%	0.0	0.0	
0-4	5-10	none	0.05	0%	0.0	0.0	
0-4	S-10	none	0.05	0%	0.0	0.0	
0-4	8-10	none	7	0%	0.0	0.0	
0-4	8-10	none	1	0%	0.0	0.0	
0-4	8-10	none	1	0%	0.0	0.0	
0-4	8-10	none	0.05	0%	0.0	0.0	
0-4	8-10	none	0.05	0%	0.0	0.0	
		MINORCA OUTF	LOW DOMIN	ATED BY CLEAR WATER	RPOOL		
5-8	5-10	none	7	39%	2.8	1.4	
5-8	5-10	none	7	28%	.2.5	1.2	
5-8	5-10	none	1	39%	0.5	0.2	
5-8	5-10	none	1	28%	0.4	0.2	
5-8	5-10	none	0.05	39%	- 0.1	0.1	
5-8	5-10	none	0.05	28%	0.1	0.1	
5-8	8-10	none	7	39%	2.8	0.8	
5-8	8-10	none	7	28%	2.5	0.7	
5-8	8-10	none	1	39%	0.5	0.2	
5-8	8-10	none	1	28%	0.4	0.2	
5-8	8-10	none	0.05	39%	0.1	0.1	
5-8	8-10	none	0.05	28%	0.1	0.1	
					11/ . (775)		
0.10	C 10	MINORCA OUTFL	UW DOMINA	1ED BY TAILINGS PORE	WATER	1.7	
8-10	5-10	none	4	39%	2.8	1.7	
8-10	5-10	none		28%	2.5	1.4	
8-10	5-10	none		29% 29 <i>%</i>	0.3	0.3	
8 10	5 10	none	0.05	28 %	0.4	0.5	
8 10	5 10	none	0.05	28.00	0.1	0.1	
11-40	5-10	grassy vegetation	7	23.0	1.6	17	
11-40	5-10	grassy vegetation	7	18%	1.0	14	
11-40	5-10	grassy vegetation	ĺ	21%	0.3	0.3	
11-40	5-10	grassy vegetation	1 î	18%	0.3	0.3	
11-40	5-10	grassy vegetation	0.05	21%	0.2	0.1	
11-40	5-10	grassy vegetation	0.05	18%	0.2	0.1	
41-50+	5-10	forest vegetation	7	13%	1.1	1.6	
41-50+	5-10	forest vegetation	7	12%	1.0	1.4	
41-50+	5-10	forest vegetation	1	13%	0.3	0.3	
41-50+	5-10	forest vegetation	1	12%	0.3	0.3	
41-50+	5-10	forest vegetation	0.05	13%	0.2	0.2	
41-50+	5-10	forest vegetation	0.05	12%	0.2	0.2	
8-10	8-10	none	7	39%	2.8	1.3	
8-10	8-10	none	7	28%	2.5	1.1	
8-10	8-10	none	1	39%	0.5	0.2	
8-10	8-10	none	1	28%	0.4	0.2	
8-10	8-10	none	0.05	39%	0.1	0.1	
8-10	8-10	none	0.05	28%	0.1	0.1	
11-40	8-10	grassy vegetation	7	21%	1.6	1.6	
11-40	8-10	grassy vegetation	7	18%	1.4	1.5	
11-40	8-10	grassy vegetation		21%	0.3	0.3	
11-40	8-10	grassy vegetation		18%	0.3	0.3	
11-40	8-10	grassy vegetation	0.05	21%	0.2	0.1	
11-40	8-10 8-10	grassy vegetation	0.05	18%0	0.2	0.1	
41-50+	0-10	forest vegetation	1 7	13%	1.1	1.0	
41-50+	8 10	forest vegetation		1270	1.0	1.5	
41-50+	0-10 8_10	forest vegetation		1370	0.5	0.3	
41-50-	8-10	forest vegetation	0.05	12%	0.5	0.2	
41-50+	8-10	forest vegetation	0.05	12%	0.2	0.2	

, ,		<u>NU (</u>	OUTFLOW FR	OM MINORCA PIT		- // \
	Operations within the Mind	orca Pit		Missabe Mt Pit Cor	icentration Estimates (m	g/L)
Depositional	Period of Max. Outflow	Reclamation	Minorca	Minorca Contribution to	Man. Nat Innut Care	Max. Estimated Conc. in
(Yauan)	(dapasition year)	Conditions	Source Term	Missabe Net Input	Max. Net input Conc.	Time During 1nis
	(deposition year)		6	0.07	0.2 (healesseed)	
0-4	5-10	none	6	0%	0.5 (background)	0.3
0-4	5-10	none	0	0%	0.5	0.3
0-4	5-10	none		0%	0.5	0.3
0-4	5-10	none	3	0%	0.3	0.3
0-4	5-10	none		0%	0.3	0.3
0-4	5-10	none		0%	0.3	0.3
0-4	8-10	none	6	0%	0.3	0.3
0-4	8-10	none	6	0%	0.3	0.3
0-4	8-10	none	3	0%	0.3	0.3
0-4	8-10	none	3	0% .	0.3	0.3
0-4	8-10	none	1	0%	0.3	0.3
0-4	8-10	none	1	0%	0.3	0.3
		MINORCA OUTF	LOW DOMIN	ATED BY CLEAR WATER	POOL	
5-8	5-10	none	6	39%	2.5	1.3
5-8	5-10	none	6	28%	1.9	1.2
5-8	5-10	none	3	39%	1.3	0.8
5-8 '	5-10	none	3	. 28%	1.0	0.7
5-8	5-10	none	1	39%	0.6	0.4
5-8	5-10	none		28%	0.5	0.4
5-8	8-10	none	6	39%	25	0.8
58	8-10	none	6	28%	1.0	0.8
50	8-10	none		2076	1.5	0.8
5-8	8-10	none	5	3970	1.5	0.5 Q.5
5-8	8-10	none	3	28%	1.0	0.5
5-8	8-10	none		39%	0.6	0.3
5-8	8-10	none	<u> </u>	28%	0.5	0.3
		MINORCA OUTFL	OW DOMINA	TED BY TAILINGS PORE	WATER	
8-10	5-10	none	6	39%	2.5	1.6
8-10	5-10	none	6	28%	1.9	1.3
8-10	5-10	none	3	39%	1.3	0.9
8-10	5-10	none	3	28%	1.0	0.8
8-10	5-10	none	1	39%	0.6	0.4
8-10	5-10	none	1	28%	0.5	0.4
11-40	5-10	grassy vegetation	6	21%	1.5	1.6
11-40	5-10	grassy vegetation	6	18%	1.3	1.3
11-40	5-10	grassy vegetation	3	21%	0.9	0.9
11-40	5-10	grassy vegetation	3	18%	0.7	0.8
11-40	5-10	grassy vegetation	1	21%	0.4	0.4
11-40	5-10	grassy vegetation	1	18%	0.4	0.4
41-50+	5-10	forest vegetation	6	13%	1.0	1.5
41 50+	5 10	forest vegetation	6	12%	1.0	1.3
41.50	5 10	forest vegetation	2	1270	1.0	1.5
41-50+	5-10	forest vegetation	5	13%	0.0	0.9
41-50+	5-10	forest vegetation	3	12%	0.0	0.8
41-50+	5-10	forest vegetation		13%	0.4	0.4
41-50+	5-10	torest vegetation		12%	0.4	0.4
8-10	8-10	none	6	39%	2.5	1.2
8-10	8-10	none	6	28%	1.9	1.1
8-10	8-10	none	3	39%	1.3	0.7
8-10	8-10	none	3	28%	1.0	0.6
8-10	8-10	none	1	39%	0.6	0.4
8-10	8-10	none	1	28%	0.5	0.4
11-40	8-10	grassy vegetation	6	21%	1.5	1.5
11-40	8-10	grassy vegetation	6	18%	1.3	1.3
11-40	8-10 .	grassy vegetation	3	21%	0.9	0.8
11-40	8-10	grassy vegetation	3	18%	0.7	0.7
11-40	8-10	grassy vegetation	1 1	21%	0.4	0.4
11-40	8-10	grassy vegetation	i i	18%	0.4	0.4
41 50+	8,10	forest vegetation	6	120%	10	1 4
41 50+	8_10	forest vegetation	6	120%	10	1 2
41-50+	0-10	forest vegetation	1 1	1270	1.0	1.2
41-30+	0-10	forest vegetation		1370	0.0	0.0
41-50+	8-1U	forest vegetation	3	1270	0.0	0.7
41-50+	8-10	rorest vegetation		13%	0.4	0.4
41-50+	8-10	torest vegetation	1 1	12%	0.4	0.4

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Table A3.2.Summary of approaches used to estimate maximum impact on fluoride levels<br/>in the Missabe Mountain Pit. Concentrations in mg/L.

Depresention         Prend of Max Conflow         Control         Constant of a Conflored         Minorea	Operations within the Minazon Bit			OUTFLOW FROM MINORCA PIT Missiba Mt Bit Concentration Estimates (ug/L)			
Time Frend         Immoreal         Minoreal         Minoreal	Denositional	Period of Max Outflow	nca rit,	<i></i>	MISSAUE MILTICO	incentration Estimates (u)	Max Estimated Conc. in
$ \begin{array}{ c c c c c c c c c c c c c c c c c c c$	Time Period (Years)	from Minorca (deposition year)	Reclamation Conditions	Minorca Source Term	Minorca Contribution to Missabe Net Input	Max. Net Input Conc.	Missabe During This Time Period
$\begin{array}{c c c c c c c c c c c c c c c c c c c $	0-4	5-10	none	130	0%	0.4 (background)	0.4
$\begin{array}{c c c c c c c c c c c c c c c c c c c $	0-4	5-10	none	130	0%	0.4	0.4
$\begin{array}{c c c c c c c c c c c c c c c c c c c $	0-4	5-10	none	45	0%	0.4	0.4
$\begin{array}{c c c c c c c c c c c c c c c c c c c $	0-4	5-10	none	45	0%	0.4	0.4
$\begin{array}{c c c c c c c c c c c c c c c c c c c $	0-4	5-10	none	15	0%	0.4	0.4
$\begin{array}{c c c c c c c c c c c c c c c c c c c $	0-4	5-10	none	15	0%	0.4	0.4
$\begin{array}{c c c c c c c c c c c c c c c c c c c $	0-4	8-10	none	130	0%	0.4	0.4
$\begin{array}{c c c c c c c c c c c c c c c c c c c $	0-4	8-10	none	130	0%	0.4	0.4
$\begin{array}{c c c c c c c c c c c c c c c c c c c $	0-4	8-10	none	45	0%	0.4	0.4
$\begin{array}{c c c c c c c c c c c c c c c c c c c $	0-4	8-10	none	45	0%	0.4	0.4
0-4         8-10         none         15         0%         0.4         0.4           5-8         5-10         none         130         39%         51         25           5-8         5-10         none         45         39%         13         7           5-8         5-10         none         45         28%         13         7           5-8         5-10         none         45         28%         4         3           5-8         5-10         none         15         39%         6         3           5-8         8-10         none         130         28%         37         12           5-8         8-10         none         130         28%         5         3           5-8         8-10         none         130         28%         13         4           5-8         8-10         none         130         39%         6         2           5-8         8-10         none         130         39%         51         25           8-10         5-10         none         130         39%         6         4           8-10         5-10         non	0-4	8-10	none	15	0%	0.4	0.4
$\begin{tabular}{ c c c c c c c c c c c c c c c c c c c$	0-4	8-10	none	15	0%	0.4	0.4
$\begin{array}{c c c c c c c c c c c c c c c c c c c $			MINORCA OUTF	LOW DOMIN	ATED BY CLEAR WATER	POOL	
$\begin{array}{c c c c c c c c c c c c c c c c c c c $	5-8	5-10	none	130	39%	51	25
$\begin{array}{c c c c c c c c c c c c c c c c c c c $	5-8	5-10	none	130	28%	37	21
$\begin{array}{c ccccccccccccccccccccccccccccccccccc$	5-8	5-10	none	45 .	39%	18	9
$\begin{array}{c ccccccccccccccccccccccccccccccccccc$	5-8	5-10	none	45	28%	13	7
$\begin{array}{c ccccccccccccccccccccccccccccccccccc$	5-8	5-10	none	15	39%	6	3
$\begin{array}{c ccccccccccccccccccccccccccccccccccc$	5-8	5-10	none	15	28%	4	3
3-3         6-10         none         150         2.5%         37         12           5-8         8-10         none         45         28%         13         4           5-8         8-10         none         15         28%         4         2           5-8         8-10         none         15         28%         4         2           MINORCA CUTFLOW DOMINATED BY TAILINGS PORE WATER           8-10         5-10         none         15         28%         4         2           8-10         5-10         none         130         28%         37         21           8-10         5-10         none         45         39%         18         11           8-10         5-10         none         15         39%         6         4           8-10         5-10         none         15         28%         4         3           11-40         5-10         grassy vegetation         130         21%         24         18           11-40         5-10         grassy vegetation         15         13%         3         3           11-40         5-10         grassy vegetation         15 </td <td>2-8 5 9</td> <td>8-10</td> <td>none</td> <td>130</td> <td>39%</td> <td>21</td> <td>13</td>	2-8 5 9	8-10	none	130	39%	21	13
$\begin{array}{c ccccccccccccccccccccccccccccccccccc$	5.0	8-10	none	150	28%	37	12
2-3         5-10         1000         15         2.5%         15         4           5-8         8-10         none         15         28%         4         2           MINORCA CUTFLOW DOMINATED BY TAILINGS PORE WATER           8-10         5-10         none         130         28%         51         25           8-10         5-10         none         45         39%         66         2           8-10         5-10         none         45         39%         18         11           8-10         5-10         none         45         39%         66         4           8-10         5-10         none         15         39%         66         4           8-10         5-10         none         15         29%         4         3           11-40         5-10         grassy vegetation         130         21%         28         22           11-40         5-10         grassy vegetation         15         18%         8         9           11-40         5-10         grassy vegetation         15         18%         3         4           11-40         5-10         forest vegetation	50	8-10	none	45	39%	10	3
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8-10 $8-10$ none $130$ $28%$ $37$ $12$ $8-10$ $8-10$ none $45$ $39%$ $18$ $8$ $8-10$ $8-10$ none $45$ $28%$ $13$ $7$ $8-10$ $8-10$ none $15$ $39%$ $6$ $3$ $8-10$ $8-10$ none $15$ $28%$ $4$ $2$ $11-40$ $8-10$ grassy vegetation $130$ $21%$ $28$ $14$ $11-40$ $8-10$ grassy vegetation $130$ $18%$ $24$ $12$ $11-40$ $8-10$ grassy vegetation $45$ $21%$ $10$ $10$ $11-40$ $8-10$ grassy vegetation $45$ $21%$ $3$ $3$ $11-40$ $8-10$ grassy vegetation $15$ $21%$ $3$ $3$ $11-40$ $8-10$ grassy vegetation $15$ $21%$ $3$ $3$ $11-40$ $8-10$ grassy vegetation $15$ $18%$ $3$ $3$ $11-40$ $8-10$ grassy vegetation $15$ $18%$ $3$ $3$ $11-40$ $8-10$ grassy vegetation $15$ $18%$ $3$ $3$ $11-40$ $8-10$ forest vegetation $130$ $12%$ $6$ $9$ $41-50+$ $8-10$ forest vegetation $130$ $12%$ $6$ $8$ $41-50+$ $8-10$ forest vegetation $45$ $12%$ $6$ $8$ $41-50+$ $8-10$ forest vegetation $45$ $12%$ $6$	8-10	8-10	none	130	39%	51	14
8-10 $8-10$ none $45$ $39%$ $18$ $8$ $8-10$ $8-10$ none $45$ $28%$ $13$ $7$ $8-10$ $8-10$ none $15$ $39%$ $6$ $3$ $8-10$ $8-10$ none $15$ $28%$ $4$ $2$ $11-40$ $8-10$ grassy vegetation $130$ $21%$ $28$ $14$ $11-40$ $8-10$ grassy vegetation $130$ $18%$ $24$ $12$ $11-40$ $8-10$ grassy vegetation $45$ $21%$ $10$ $10$ $11-40$ $8-10$ grassy vegetation $45$ $21%$ $10$ $10$ $11-40$ $8-10$ grassy vegetation $15$ $21%$ $3$ $3$ $11-40$ $8-10$ grassy vegetation $15$ $18%$ $8$ $8$ $11-40$ $8-10$ grassy vegetation $15$ $18%$ $3$ $3$ $11-40$ $8-10$ grassy vegetation $15$ $18%$ $3$ $3$ $11-40$ $8-10$ grassy vegetation $15$ $18%$ $3$ $3$ $11-50+$ $8-10$ forest vegetation $130$ $12%$ $16$ $9$ $41-50+$ $8-10$ forest vegetation $45$ $13%$ $6$ $8$ $41-50+$ $8-10$ forest vegetation $45$ $12%$ $6$ $8$ $41-50+$ $8-10$ forest vegetation $45$ $13%$ $2$ $3$ $41-50+$ $8-10$ forest vegetation $15$ $13%$ </td <td>8-10</td> <td>8-10</td> <td>none</td> <td>130</td> <td>28%</td> <td>37</td> <td>12</td>	8-10	8-10	none	130	28%	37	12
8-10 $8-10$ none $45$ $28%$ $13$ $7$ $8-10$ $8-10$ none $15$ $39%$ $6$ $3$ $8-10$ $8-10$ none $15$ $28%$ $4$ $2$ $11-40$ $8-10$ grassy vegetation $130$ $21%$ $28$ $14$ $11-40$ $8-10$ grassy vegetation $130$ $18%$ $24$ $12$ $11-40$ $8-10$ grassy vegetation $45$ $21%$ $10$ $10$ $11-40$ $8-10$ grassy vegetation $45$ $18%$ $8$ $8$ $11-40$ $8-10$ grassy vegetation $15$ $18%$ $3$ $3$ $11-50+$ $8-10$ forest vegetation $130$ $12%$ $16$ $9$ $41-50+$ $8-10$ forest vegetation $45$ $13%$ $6$ $8$ $41-50+$ $8-10$ forest vegetation $45$ $12%$ $6$ $8$ $41-50+$ $8-10$ forest vegetation $45$ $12%$ $6$ $8$ $41-50+$ $8-10$ forest vegetation $15$ $13%$ $2$ $3$ $41-50+$ $8-10$ forest vegetation $15$ <td>8-10</td> <td>8-10</td> <td>none</td> <td>45</td> <td>39%</td> <td>18</td> <td>8</td>	8-10	8-10	none	45	39%	18	8
8-10 $8-10$ none $15$ $39%$ $6$ $3$ $8-10$ $8-10$ none $15$ $28%$ $4$ $2$ $11-40$ $8-10$ grassy vegetation $130$ $21%$ $28$ $14$ $11-40$ $8-10$ grassy vegetation $130$ $18%$ $24$ $12$ $11-40$ $8-10$ grassy vegetation $45$ $21%$ $10$ $10$ $11-40$ $8-10$ grassy vegetation $45$ $21%$ $3$ $3$ $11-40$ $8-10$ grassy vegetation $45$ $18%$ $8$ $8$ $11-40$ $8-10$ grassy vegetation $15$ $21%$ $3$ $3$ $11-40$ $8-10$ grassy vegetation $15$ $18%$ $3$ $3$ $11-40$ $8-10$ grassy vegetation $15$ $18%$ $3$ $3$ $11-40$ $8-10$ grassy vegetation $15$ $18%$ $3$ $3$ $11-40$ $8-10$ forest vegetation $15$ $18%$ $3$ $3$ $41-50+$ $8-10$ forest vegetation $130$ $12%$ $16$ $9$ $41-50+$ $8-10$ forest vegetation $45$ $13%$ $6$ $8$ $41-50+$ $8-10$ forest vegetation $45$ $12%$ $6$ $8$ $41-50+$ $8-10$ forest vegetation $15$ $13%$ $2$ $3$ $41-50+$ $8-10$ forest vegetation $15$ $13%$ $2$ $3$ $41-50+$ $8-10$ forest vegetation <td>8-10</td> <td>8-10</td> <td>none</td> <td>45</td> <td>28%</td> <td>13</td> <td>7</td>	8-10	8-10	none	45	28%	13	7
8-10 $8-10$ none15 $28%$ 42 $11-40$ $8-10$ grassy vegetation $130$ $21%$ $28$ $14$ $11-40$ $8-10$ grassy vegetation $130$ $18%$ $24$ $12$ $11-40$ $8-10$ grassy vegetation $45$ $21%$ $10$ $10$ $11-40$ $8-10$ grassy vegetation $45$ $18%$ $8$ $8$ $11-40$ $8-10$ grassy vegetation $15$ $21%$ $3$ $3$ $11-40$ $8-10$ grassy vegetation $15$ $21%$ $3$ $3$ $11-40$ $8-10$ grassy vegetation $15$ $18%$ $3$ $3$ $41-50+$ $8-10$ forest vegetation $130$ $13%$ $17$ $10$ $41-50+$ $8-10$ forest vegetation $130$ $12%$ $16$ $9$ $41-50+$ $8-10$ forest vegetation $45$ $13%$ $6$ $9$ $41-50+$ $8-10$ forest vegetation $45$ $13%$ $2$ $3$ $41-50+$ $8-10$ forest vegetation $45$ $13%$ $2$ $3$ $41-50+$ $8-10$ forest vegetation $15$ $13%$ $2$ $3$	8-10	8-10	none	15	39%	6	3
11-408-10grassy vegetation130 $21%$ 2814 $11-40$ 8-10grassy vegetation130 $18%$ $24$ $12$ $11-40$ 8-10grassy vegetation $45$ $21%$ $10$ $10$ $11-40$ 8-10grassy vegetation $45$ $21%$ $3$ $3$ $11-40$ 8-10grassy vegetation $15$ $21%$ $3$ $3$ $11-40$ 8-10grassy vegetation $15$ $21%$ $3$ $3$ $41-50+$ 8-10forest vegetation $130$ $13%$ $17$ $10$ $41-50+$ 8-10forest vegetation $130$ $12%$ $16$ $9$ $41-50+$ 8-10forest vegetation $45$ $13%$ $6$ $9$ $41-50+$ 8-10forest vegetation $45$ $12%$ $6$ $8$ $41-50+$ 8-10forest vegetation $45$ $12%$ $6$ $8$ $41-50+$ 8-10forest vegetation $45$ $12%$ $6$ $8$ $41-50+$ 8-10forest vegetation $15$ $13%$ $2$ $3$	8-10	8-10	none	15	28%	4	2
11-40 $8-10$ grassy vegetation $130$ $18%$ $24$ $12$ $11-40$ $8-10$ grassy vegetation $45$ $21%$ $10$ $10$ $11-40$ $8-10$ grassy vegetation $45$ $18%$ $8$ $8$ $11-40$ $8-10$ grassy vegetation $15$ $21%$ $3$ $3$ $11-40$ $8-10$ grassy vegetation $15$ $18%$ $3$ $3$ $41-50+$ $8-10$ forest vegetation $130$ $13%$ $17$ $10$ $41-50+$ $8-10$ forest vegetation $130$ $12%$ $16$ $9$ $41-50+$ $8-10$ forest vegetation $45$ $13%$ $6$ $9$ $41-50+$ $8-10$ forest vegetation $45$ $12%$ $6$ $8$ $41-50+$ $8-10$ forest vegetation $15$ $13%$ $2$ $3$ $41-50+$ $8-10$ forest vegetation $15$ $13%$ $2$ $3$	11-40	8-10	grassy vegetation	130	21%	28	14
11-40 $8-10$ grassy vegetation $45$ $21%$ $10$ $10$ $11-40$ $8-10$ grassy vegetation $45$ $18%$ $8$ $8$ $11-40$ $8-10$ grassy vegetation $15$ $21%$ $3$ $3$ $11-40$ $8-10$ grassy vegetation $15$ $18%$ $3$ $3$ $11-40$ $8-10$ grassy vegetation $15$ $18%$ $3$ $3$ $41-50+$ $8-10$ forest vegetation $130$ $12%$ $16$ $9$ $41-50+$ $8-10$ forest vegetation $45$ $13%$ $6$ $9$ $41-50+$ $8-10$ forest vegetation $45$ $12%$ $6$ $8$ $41-50+$ $8-10$ forest vegetation $15$ $13%$ $2$ $3$ $41-50+$ $8-10$ forest vegetation $15$ $13%$ $2$ $3$	11-40	8-10	grassy vegetation	130	18%	24	12
11-40 $8-10$ grassy vegetation $45$ $18%$ $8$ $8$ $11-40$ $8-10$ grassy vegetation $15$ $21%$ $3$ $3$ $11-40$ $8-10$ grassy vegetation $15$ $18%$ $3$ $3$ $11-40$ $8-10$ grassy vegetation $15$ $18%$ $3$ $3$ $41-50+$ $8-10$ forest vegetation $130$ $13%$ $17$ $10$ $41-50+$ $8-10$ forest vegetation $130$ $12%$ $16$ $9$ $41-50+$ $8-10$ forest vegetation $45$ $13%$ $6$ $8$ $41-50+$ $8-10$ forest vegetation $15$ $13%$ $2$ $3$ $41-50+$ $8-10$ forest vegetation $15$ $13%$ $2$ $3$	11-40	8-10	grassy vegetation	45	21%	10	10
11-40 $8-10$ grassy vegetation $15$ $21%$ $3$ $3$ $11-40$ $8-10$ grassy vegetation $15$ $18%$ $3$ $3$ $41-50+$ $8-10$ forest vegetation $130$ $13%$ $17$ $10$ $41-50+$ $8-10$ forest vegetation $130$ $12%$ $16$ $9$ $41-50+$ $8-10$ forest vegetation $45$ $13%$ $6$ $9$ $41-50+$ $8-10$ forest vegetation $45$ $12%$ $6$ $8$ $41-50+$ $8-10$ forest vegetation $15$ $13%$ $2$ $3$ $41-50+$ $8-10$ forest vegetation $15$ $12%$ $2$ $3$	11-40	8-10	grassy vegetation	45	18%	8	8
11-408-10grassy vegetation15 $18%$ 33 $41-50+$ $8-10$ forest vegetation $130$ $13%$ $17$ $10$ $41-50+$ $8-10$ forest vegetation $130$ $12%$ $16$ $9$ $41-50+$ $8-10$ forest vegetation $45$ $13%$ $6$ $9$ $41-50+$ $8-10$ forest vegetation $45$ $12%$ $6$ $8$ $41-50+$ $8-10$ forest vegetation $15$ $13%$ $2$ $3$	11-40	8-10	grassy vegetation	15	21%	3	3
41-50+ $8-10$ forest vegetation $130$ $13%$ $17$ $10$ $41-50+$ $8-10$ forest vegetation $130$ $12%$ $16$ $9$ $41-50+$ $8-10$ forest vegetation $45$ $13%$ $6$ $9$ $41-50+$ $8-10$ forest vegetation $45$ $12%$ $6$ $8$ $41-50+$ $8-10$ forest vegetation $15$ $13%$ $2$ $3$ $41-50+$ $8-10$ forest vegetation $15$ $12%$ $2$ $3$	11-40	8-10	grassy vegetation	15	18%	3	3
41-50+ $8-10$ torest vegetation $130$ $12%$ $16$ $9$ $41-50+$ $8-10$ forest vegetation $45$ $13%$ $6$ $9$ $41-50+$ $8-10$ forest vegetation $45$ $12%$ $6$ $8$ $41-50+$ $8-10$ forest vegetation $15$ $13%$ $2$ $3$ $41-50+$ $8-10$ forest vegetation $15$ $12%$ $2$ $3$	41-50+	8-10	torest vegetation	130	13%	17	10
41-50+ $8-10$ forest vegetation $45$ $13%$ $6$ $9$ $41-50+$ $8-10$ forest vegetation $45$ $12%$ $6$ $8$ $41-50+$ $8-10$ forest vegetation $15$ $13%$ $2$ $3$ $41-50+$ $8-10$ forest vegetation $15$ $13%$ $2$ $3$	41-50+	8-10	forest vegetation	130	12%	16	9
$4_{1-50+}$ $8_{-10}$ forest vegetation $4_5$ $12\%$ $6$ $8$ $4_{1-50+}$ $8_{-10}$ forest vegetation $15$ $13\%$ $2$ $3$ $4_{1-50+}$ $8_{-10}$ forest vegetation $15$ $13\%$ $2$ $3$	41-50+	8-10	forest vegetation	45	13%	0	9
$^{+}41-50+$ $^{-}010$ 101051 Vegetation 1.5 1.5% 2 5 (1.5) $^{-}41-50+$ 8.10 for at vegetation 1.5 1.2% 2 2	41-50+	8-10	forest vegetation	45	12%	0	8
	· 41-50+ 41-50±	8-10 8-10	forest vegetation	15	13%	2	2

Table A3.3.Summary of approaches used to estimate maximum impact on molybdenum<br/>levels in the Missabe Mountain Pit. Concentrations in ug/L.

		NO	OUTELOW FR	OM MINORCA PIT		
C	perations within the M	finorca Pit		Missabe Mt Pit Co	ncentration Estimates (m	g/L)
Depositional	Period of Max.					Man Estimated Case in
Time Period	Outflow from	Reclamation Conditions	Minorca	Minorca Contribution to	Max Net Input Conc	Max. Estimated Conc. in Missabe During This
(Years)	Minorca (deposition	Rechamation Conditions	Source Term	Missabe Net Input	max. Net input cone.	Time Period
	year)			0.00	0.7.4 1 1	
0-4	5-10	none	7	0%	0.7 (background)	0.7
0-4	5-10	none	3	0%	0.7	0.7
0-4	5-10	none	3	0%	0.7	0.7
0-4	5-10	none	0.1	0%	0.7	0.7
0-4	5-10	none	0.1	0%	0.7	0.7
0-4	8-10	none	7	0%	0.7	0.7
0-4	8-10	none	7	0%	0.7	0.7
0-4	8-10	none	3	0%	0.7	0.7
0-4	8-10	none	3	0%	. 0.7	0.7
0-4	8-10	none	0.1	0%	0.7	0.7
0-4	8-10	none	0.1	070		0.7
		MINORCA OUTF	LOW DOMIN	ATED BY CLEAR WATER	POOL	
5-8	5-10	none	7	39%	3.0	1.8
5-8	5-10	none	7	28%	2.3	1.6
5-8	5-10	none	3	39%	1.5	1.1
5-8	5-10	none	3	28%	1.2	1.0
5-8	5-10	none	0.1	39%	0.4	0.6
5-8	5-10	none	0.1	28%	0.4	0.6
5-8	8-10	none	7	39%	3.0	1.3
5-8	8-10	none		28%	2.3	1.2
5-8 5-8	8-10	none	3	39%	1.5	0.9
5-8	8-10	none	01	2378	0.4	0.8
5-8	8-10	none	0.1	28%	0.4	0.7
		MINORCA OUTFL	OW DOMINA'	TED BY TAILINGS PORE	WATER	
8-10	5-10	none	7	39%	3.0	2.1
8-10	5-10	none	7	28%	2.3	1.8
8-10	5-10	none	3	39%	1.5	1.2
8-10	5-10	none	3	28%	1.2	1.0
8-10	5-10	none	0.1	39%	0.4	0.5
8-10	5-10	none	0.1	28%	0.4	0.5
11-40	5-10	grassy vegetation	7	18%	1.9	2.1
11-40	5-10	grassy vegetation	3	21%	1.7	1.0
11-40	5-10	grassy vegetation	3	18%	1.0	1.0
11-40	5-10	grassy vegetation	0.1	21%	0.4	0.5
11-40	5-10	grassy vegetation	0.1	18%	0.4	0.5
41-50+	5-10	forest vegetation	7	13%	1.3	1.9
41-50+	5-10	forest vegetation	7	12%	1.3	1.6
41-50+	5-10	forest vegetation	3	13%	0.8	1.0
41-50+	5-10	forest vegetation	3	12%	0.8	0.9
41-50+	5-10	forest vegetation	0.1	13%	0.5	0.4
41-30+	S-10 8-10	none		1270	0.5	0.4
8-10	8-10	none	7	28%	2.3	1.7
8-10	8-10	none	3	39%	1.5	1.0
8-10	8-10	none	3	28%	1.2	0.9
8-10	8-10	none	0.1	39%	0.4	0.6
8-10	8-10	none	0.1	28%	0.4	0.6
11-40	8-10	grassy vegetation	7	21%	1.9	1.9
11-40	8-10	grassy vegetation	7	18%	1.7	1.6
11-40	8-10	grassy vegetation	3	21%	1.0	1.0
11-40	8-10	grassy vegetation	3	18%	1.0	0.9
11-40	0-10 8_10	grassy vegetation	0.1	180%	0.4	0.5
41-50+	8-10	forest vegetation	7	13%	1.3	1.8
41-50+	8-10	forest vegetation	7	12%	1.3	1.6
41-50+	8-10	forest vegetation	3	13%	0.8	1.0
41-50+	8-10	forest vegetation	3	12%	0.8	0.9
41-50+	8-10	forest vegetation	0.1	13%	. 0.5	0.4
41-50+	8-10	forest vegetation	0.1	12%	0.5	0.4

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Table A3.4.Summary of approaches used to estimate maximum impact on arsenic levels<br/>in the Missabe Mountain Pit. Concentrations in ug/L.

Data Source	Condition	Designator	Duration of Elevated Mn (months)	Mn (mg/L)
Tank	Surface water above taconite	Tank 3	2 - 9.5	0.00
Experiments	atmosphere	Tank 4	4 - 9.5	0.01
Mn Oxidation Experiments	Tailings pore water mixed with oxidized pit water and exposed	100% pore water	nd	3.2
	to the atmosphere	50% pore water	. 3.5	0.01
		24% pore water	1.75	0.01
		12.5% pore water	1.75	0.00
		2.5% pore water	1.75	0.01
Pierce and Tomcko, 1989	Field measurements in existing pit lakes	Embarrass Pit	na	0.01
		Forsyth Pit	na	22.5
		Gilbert Pit	na	<0.01
		Kinney Pit	na	0.25
		Miners Pit	na	4.3
		St. James Pit	na	0.02
		Stubler Pit	na	0.13
		Tioga Pit	na	< 0.01

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Table A3.5.Summary of manganese oxidation information and data.

"nd" = not determined "na" = not applicable