ATTACHMENT 2
EVALUATION OF STRATIFICATION AND DISSOLVED OXYGEN

1.0 STRATIFICATION AND MIXING IN THE CONTINENTAL PIT LAKE

An important aspect of the Continental Pit Lake will be how water in the pit stratifies and mixes. There are two types of density stratification that can occur in pit lakes, thermal stratification that occurs on a seasonal basis in nearly all lakes, and TDS/salinity stratification that persists continuously for years in only a small percentage of lakes. Intermittent or permanent stratification is important because it regulates the delivery of dissolved oxygen (DO) from surface waters that are in contact with the atmosphere, to the deeper isolated waters. The presence of DO controls the oxidation-reduction potential of the water, which affects not only the weathering of pyrite, but also the speciation of redox-sensitive elements. In order to appropriately specify the oxidation-reduction potential for geochemical modeling and to determine whether inundated pyrite will continue to oxidize, the stratification pattern, as well as oxygen sources and sinks must be determined. Therefore, these internal physical processes were evaluated to determine whether the model should include them as transient boundaries and processes within the primary system boundaries, depending on whether they lead to different chemical processes in different layers of the lake.

An unstratified water column for the Continental pit is not considered because this condition typically occurs in either shallow lakes (<10 meters) or in tropical/equatorial regions. There are two scenarios for a stratified water column that can provide an environment where DO can be depleted. By far the most common scenario for temperate, mid-latitude lakes like the Continental pit lake, is a water column that seasonally stratifies in the summer and winter, and mixes in the spring and fall each year (dimictic circulation pattern) due to temperature driven density differences. The other condition that is less common is a water column that permanently stratifies (meromictic circulation pattern) due to TDS driven density differences. In this case, the overlying low TDS water may still stratify thermally. In both dimictic and meromictic lakes, the dissolved oxygen can become depleted in the deeper isolated water through a variety of microbial and chemical processes.

2.0 PERMANENT SALINITY STRATIFICATION (MEROMIXIS)

Permanent stratification occurs when the salinity (and therefore density) of the deepest water is so much higher than the overlying water that the two layers cannot be mixed by typical environmental processes. The term TDS is used instead of salinity because salinity traditionally refers to waters in which sodium and chloride are the major ions, whereas in the Continental pit calcium and sulfate will be the major ions. In studying 160 natural meromictic lakes, Anderson et al., (1985) used the classifications of Walker and Likens (1975) to identify the following types of conditions that can lead to or maintain meromixis.

- Types 1 and 2 require inflow of fresh water over a pre-existing layer of saline water, or inflow of saline/turbid water that plunges under a layer of fresh water. The Contintental pit does not have conditions that would create either Type 1 or 2 meromixis. When the TDS of the lake eventually becomes high (2,000 to 5,000 mg/L) by evaporation, the fresh water inputs from precipitation (TDS = 0) and wall rock runoff (TDS = 500 mg/L) is so slow and dispersed that it will be quickly mixed in with the main water body. Further, if precipitation and runoff did float on the top, the high evaporation to precipitation ratio (3:1) would prevent a freshwater layer from ever building up. The Continental pit also lacks any high TDS inflows that could plunge to the bottom. Water that enters the lake at the surface does so as intermittent and dispersed sources. Precipitation events in the region rarely produce 2 cm of accumulation. These small events are not large enough event to produce a thick enough layer on the surface to initiate stable stratification.
- Type 3 is created by subsurface inflow of either low or high salinity water. The TDS of ground water entering the Continental pit is 750 mg/L, which is equal to or lower than the TDS of the pit lake water, which increases over time from 750 to 5,000 mg/L. When ground water enters the pit through cracks in the wall rock, it enters at a speed of about 0.005 feet/day. Because the ground water enters the pit in a diffuse manner (from all wall surfaces), these small trickles do not form a coherent plume that can float to the water surface and form a stable layer. Rather, the small trickles will be mixed into the main body of water.
- Type 4 requires protection from wind mixing, and chemical stratification caused by biological activity.
- Type 5 requires freezing out of salts at the surface with settling of salts to deeper water and dissolution. This process has not been observed in any lakes.

Solutes will be produced by the oxidation of pyrite and dissolution of limestone in the hypolimnion, which will increase the TDS of the hypolimnion during stratification. However, because these same reactions will occur in the epilimnion, a gradient of TDS between the epilimnion and hypolimnion will not develop. With respect to the characteristics needed for permanent TDS stratification, and the nature of the inflows to the Continental pit, the resulting lake has a very low potential for developing permanent TDS stratification.

An empirical approach was suggested by Lyons et al (1994), and Doyle and Runnells (1997), to determine whether a pit lake will stratify permanently even without salinity stratification. The approach uses the ratio of maximum lake depth to diameter (the relative depth) to reflect the tendency of the water column to vertically mix. The idea being that wind sheer applied across a lake surface provides the energy for vertical mixing, and that the greater the depth is, in relation to the distance the wind applies energy to the water, the harder it is for that energy to penetrate all the way to the bottom. Castendyk and Webster-Brown, (2007) tested this approach on 22 existing pit lakes and found no predictive relationship between observed mixing regimes and relative depth through a broad range of relative depths. The relative depth approach does not include a thermal balance on the water column or accounting of the differences in quantities and densities of the water sources.

3.0 THERMAL STRATIFICATION

Although the Continental pit lake lacks the characteristics known to cause permanent TDS stratification, it is expected to thermally stratify seasonally like other lakes in the region. Two mechanistic models have been used to predict stratification in pit lakes, CE-THERM, and DYRESM. CE-THERM is a two-dimensional model, and DYRESM (Center for Water Research, 1995) is a one-dimensional model. Both of these physical models were developed for simulating temperature profiles in reservoirs and are often coupled to water quality models that simulate algae growth and dissolved oxygen, in order to determine from what depths water can be released. Both models require substantial climatological data sets along with the density and quantities of inflows and depths of water withdrawal. Even with a thermally stratified water column, it may not be necessary to simulate the physical separation of the water column into an epilimnion and hypolimnion in the pit lake chemistry model, if the chemical processes in both layers are the same. So, before using either of these models to make predictions of thermal stratification, it is important to determine whether a thermally stratified water column is likely to result in an anoxic hypolimnion.

First, the two hypolimnetic dissolved oxygen scenarios and how they affect the modeling approach are discussed.

1. Hypolimnetic oxygen becomes depleted.

   The resulting condition is that the oxidation-reduction potential (redox) would decrease, and pyrite would not oxidize and some iron (III) precipitates would be dissolved. This scenario would require the pit lake chemistry model to seasonally switch the water column from stratified to mixed. At some point during the period of stratification, when the dissolved oxygen (DO) is depleted, the pit lake model would stop pyrite oxidation in the hypolimnion and start iron reduction. Iron reduction would continue until turnover, at which time the epilimnion and hypolimnion are mixed and the whole water column is oxygenated. So, this scenario requires periodic stratification and mixing of the water column in the pit lake model.

2. Hypolimnetic oxygen is not depleted.

   The resulting condition is that the redox potential remains high, and inundated pyrite in both the epilimnion and hypolimnion would oxidize and iron (III) precipitates would remain stable. Aside from hypolimnion having a slightly cooler temperature than the epilimnion in the summer, the chemical weathering conditions (in particular the redox potential) in the hypolimnion and epilimnion are the same. So, this scenario does not require the pit lake chemistry model to periodically switch between stratified and mixed.

4.0 ASSESSMENT OF DISSOLVED OXYGEN

In lakes, oxygen is supplied by contact with the atmosphere or generated through photosynthesis by algae in the water column. However, when stratified the hypolimnion is isolated from the atmosphere and usually light does not penetrate adequately to drive significant photosynthesis in the hypolimnion. So unlike the epilimnion, the hypolimnion does not have a continual oxygen source during stratification. If there are enough oxygen consuming processes in the hypolimnion, it is possible for all the oxygen to be consumed before turnover can oxygenate the whole water column.

In lakes the main oxygen consuming material is organic carbon produced by algae. Detrital algae settle into the hypolimnion where microbes degrade the organic matter using DO, which, if there is enough settling algae, will consume all of the DO. In the Continental pit, oxygen can also be consumed by oxidation of pyrite. The growth of algae requires sunlight, CO_2, the major nutrients nitrogen and phosphorus, and micro-nutrients. Numerous studies have shown that in the majority of lakes, primary productivity is limited by the availability of phosphorus (Wetzel, 2001, Chapra, 2005), especially the soluble inorganic form, phosphate (PO_4^{-3}). The concentration of phosphorus largely determines the productivity, or trophic conditions, of a lake, which has a strong influence on DO concentrations in the hypolimnion. Oligotrophic (low productivity) lakes have low phosphorus concentrations (<10 μg/L) and maintain DO above 80% saturation, while mesotrophic lakes have moderate phosphorus concentrations (10 to 20 μg/L) and have DO between 10% and 80% saturation, and eutrophic lakes have high phosphorus concentrations (>20 μg/L) with DO concentrations less than 10% of saturation. Total phosphorus is made up of many forms of P, including inorganic phosphate species ($H_2PO_4^-$, HPO_4^{-2}, PO_4^{-3}), and particulate and dissolved organic forms (e.g., algae, detritus and ATP, DNA etc.). The concentration of phosphorus in the Continental pit lake can be estimated based on the chemistry of the water that will develop in the pit. Due to the circumneutral pH and high concentrations of calcium that will develop in the Continental pit lake water, precipitation of the mineral hydroxyapatite ($(Ca)_5(PO_4)_3OH$) will control the dissolved inorganic phosphorus concentration. The published solubility products for hydroxyapatite range from 10^{-57} to 10^{-60} (Kaufman, 1979). To be conservative, a larger value is used in our calculations, and the solubility product is:

$$K_{sp} = [Ca]^5 \times [PO4]^3 \times [OH] = 10^{-57}$$

Solving for the concentration of phosphate,

$$[PO_4] = \left(\frac{10^{-57}}{([Ca]^5[OH])} \right)^{-3}$$

As shown in Tables 16 and 19, the pH of the lake is predicted to be approximately 8.0 ([OH] = 10^{-6} M), and the concentration of calcium will range from about 130 mg/L (0.0033 M) at 5 years to 300 mg/L (0.0075 M) during the first 100 years of pit filling. Using these values, the concentration of phosphate will be about 0.00006 to 0.00002 µg/L (10^{-13} M). In lakes with limestone geology (similar to the Continental pit), the inorganic forms comprise between 6 and 13% of the total P (Wetzel, 2001). Assuming that the inorganic phosphate comprises only 5%, the total P can be estimated as about 20-times the phosphate concentration, or about 0.001 µg/L. Further reducing the concentration is the strong sorption by ferrihydrite that will form from pyrite oxidation. For these reasons, it is expected that the Continental pit lake will be oligotrophic and that DO will not be depleted in the hypolimnion by degradation of algal detritus

Because both the epilimnion and hypolimnion are expected to remain oxic, the same chemical processes will occur in both, and it is unnecessary to include thermal stratification and mixing in the Continental pit lake model. The effect of this simplification is that all solutes are uniformly distributed throughout the water column.

5.0 REFERENCES

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