0.   EXECUTIVE SUMMARY

The *research reported will be applied* in the environmental review and permitting of future nonferrous mines in Minnesota, particularly those in the Duluth Complex. These regulatory activities require prediction of solute release from waste rock during mine operation and in the decades and centuries following mine closure. As a foundation for such predictions, the reactions occurring in waste rock stockpiles and variables affecting these reactions must be understood. This knowledge and a description of the proposed method of waste rock disposal are necessary to 1) design appropriate tests for predicting the release of potential pollutants from waste rock, 2) extrapolate results of such tests to field conditions, and 3) if necessary, implement mitigation measures that will ensure that water resources are not adversely impacted. In the present project, laboratory studies were conducted to examine solute release and variables affecting this release from waste rock from the Partridge River intrusion of the Duluth Complex. The studies provide scientific and technical information necessary to address questions inherent to environmental review and permitting of nonferrous metal mines. The project also provides empirical data describing eight years of rock dissolution for comparison with and extrapolation of data submitted for environmental review and permitting by companies proposing mining in the Duluth Complex.

To *summarize* the laboratory work, dissolution tests were initiated in August 2003 on 10 well-characterized (particle size, chemical composition, mineral content, mineral chemistry) Duluth Complex rock samples from the Babbitt and Dunka Road prospects of the Partridge River intrusion. Dissolution tests were conducted on 10 coarse samples (d < 6.35 mm = 0.25 in.; 0.13 ≤ %S ≤ 1.36) and seven fine samples (0.053 < d < 0.149 mm; 0.07 ≤ %S ≤ 0.94). The experiments remain in progress and the following report presents data generated through week 400. This report summarizes results and provides a conceptual structure to frame these results.

In general, drainage pH tended to decrease and release rates of heavy metals (copper, nickel, cobalt, zinc) and major cations (calcium, magnesium, sodium, potassium) tended to increase with increasing sulfur content. These results were consistent with the previously reported 1) dependence of sulfide mineral oxidation (as reflected by sulfate release) and the attendant acid production on the amount of sulfide minerals present and 2) importance of sulfide mineral oxidation as a driving force for release of heavy metals and major cations. More specifically, numerous relationships between drainage quality and both solid-phase sulfur content and dissolution time were identified and quantified to quantitatively describe solute release and its dependence on solid-phase composition and dissolution time.

For the 10 coarse samples, drainage pH decreased with increasing sulfur content, with a minimum value of 4.1. For all but the two highest sulfur samples, pH decreased throughout the eight-year experiment. Rates of sulfate release, reflecting sulfide mineral oxidation, increased with increasing sulfur content. The strong correlation between average annual rates for the 10 samples and corresponding sulfur contents was quantified for each year using regression analysis ($0.91 < r^2 < 0.94$). This analysis was used to derive composite annual sulfate release rates (per gram sulfur), which were found to decrease slightly over the eight-year experiment.

Release rates for copper, nickel, cobalt, and zinc also correlated highly with sulfur content (typically $0.80 < r^2 < 0.95$). Magnesium was the dominant cation released, followed by calcium, and sodium. Their releases tended to parallel that of sulfate, reflecting silicate minerals dissolving to neutralize acid produced by iron sulfide mineral oxidation.

Similar analysis was conducted on data generated in the seven fine-grained samples. As with the larger particles, drainage pH decreased and release rates for sulfate, heavy metals, and major cations increased with increasing sulfur content. Although the relationship between minimum drainage pH and sulfur content was similar to that for the larger particles, pH from the finer samples declined more rapidly, reaching minimums between weeks 60 and 120. Sulfate release from the fine particles were initially three times those from the coarse particles, reflecting the greater sulfide mineral surface area per unit mass of the fine particles, and this rapid release contributed to the aforementioned early pH depression. Sulfate release rates from the fine particles decreased fairly quickly over time and by year seven equaled those from the coarse particles, for which rates decreased more slowly. The rapid decline of rates from the fine particles was attributed to sulfur depletion and probable coating of sulfide minerals.

Dissolution testing of Dunka Road samples was limited to one sample in the 0.053-0.149 mm size fraction and three samples in the d < 6.35 mm fraction. The most notable difference between Dunka Road and Babbitt prospect rock was elevated heavy metal release from the latter. Whereas some of the difference could be ascribed to higher metal content of the Babbitt prospect rock examined, differences between prospects in total sulfide mineral oxidation rates and drainage pH also played a role. Because the number of samples for comparison was limited, these results should be viewed as preliminary.

The Partridge River rock samples yielded higher sulfate rates than Partridge River tailings of similar sulfur content, due to greater exposure of sulfide minerals in the rock samples. Heavy metal release from the rock was also higher than that from the tailings. This was due to the aforementioned elevated sulfide mineral exposure, higher heavy metal contents, and lower drainage pH associated with the rock samples. Drainage pH from the Partridge River rock tended to be about 0.7 units higher than that from previously tested South Kawishiwi rock of similar sulfur content. This was attributed to the higher heavy metal content (and consequent lower iron sulfide content) of the Partridge River rock examined in the present study.

In *conclusion,* for both ten coarse and seven fine samples, testing generated data describing drainage pH and release of sulfate, heavy metals, and major cations over a period of eight years. Drainage pH and solute release were correlated with solid-phase sulfur content and time of dissolution. Furthermore, the two data sets allowed comparison of solute release from the two size fractions, consequently providing insight on the influence of particle size. In total, the project 1) quantifies the dependence of drainage pH and release rates of sulfate, heavy metals, and major cations on solid-phase sulfur content, dissolution time, and particle size; 2) interprets results with respect to mineral dissolution reaction; and 3) provides context for the results generated by comparisons with dissolution data on Partridge River tailings and South Kawishiwi intrusion rocks. Thus, the project will help inform design of predictive test programs for

environmental review and permitting and interpretation of results generated by such program. It also provides a robust empirical data base to provide a benchmark for data submitted.

Additional work should be conducted to further the benefits generated to date. This includes continued dissolution testing to confidently define long-term trends, analysis of leached solids to increase understanding of chemical reactions controlling solute release (e.g. chemical precipitation and adsorption), and more detailed analysis of the present data, including calculation of mineral dissolution rates. Calculation of mineral dissolution rates will facilitate application of the data generated to a wider range of mineralogical compositions of Duluth Complex rock.