Technical Memorandum

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To: Mahesh Vidyasagar and Ted Eary, MFG, Inc.
Joe Maki, Michigan DEQ.

From: David Sainsbury, Itasca Consulting Group, Inc.

Re: Technical Review — Crown Pillar Subsidence and Hydrologic Stability Assessment for the Proposed Eagle Mine ***(DRAFT)***

Ref: ICG06-2376-25TM

The objective of this review is to determine whether the conclusions made within the Eagle Project Mining Permit Application regarding crown pillar subsidence and hydrologic stability are defensible.

Due to the difficulties associated with determining the mechanical properties of a particular rock mass, mining rock mechanics can be a subjective science. However, many best-practice data collection and analysis techniques have been established to eliminate many of the uncertainties associated with prediction of the response of a rock mass to mining.

The analysis techniques used to assess the crown pillar stability of Eagle Mine do not reflect industry best-practice. In addition, the hydrologic stability of the crown pillar has not been considered. Therefore, the conclusions made within the Eagle Project Mining Permit Application regarding crown pillar subsidence are not considered to be defensible.

The Scaled Span analysis conducted clearly indicates that stability of the proposed Eagle crown pillar should be a concern, although this concern has not been raised within the conclusions of the Eagle Project Geotechnical Study. Considering the sensitive nature of the hydrological environment surrounding the Eagle project, further detailed analysis is required to understand fully the expected short- and long-term crown pillar subsidence and hydrologic stability.

Specific issues that impact the conclusions made regarding the crown pillar stability of Eagle Mine are detailed below.

Intact Rock Strength Determination

- The point-load strength test is used as an index test for strength classification of rock materials. The ASTM Standard Test Method D 5731 95 [2] states, however, that point-load test results alone should not be used for design or analytical purposes. During the Eagle Mine Geotechnical Study, point load test data alone was used to estimate the intact strength of rock mass units investigated within the Mine. Unconfined compressive strength (UCS) tests were not used to calibrate the point-load test results.

- The approach used to estimate the intact rock strength is not consistent with industry best-practice and causes significant uncertainty with the rock-mass classification rating applied to each unit. This, in turn, has an effect upon all subsequent design calculations that rely upon the rock mass rating, as well as the determination of rock-mass mechanical properties for numerical modeling.

- Laboratory testing of the unconfined compressive strength (UCS) of representative intact rock specimens is required to determine the intact rock strength of the rock mass units surrounding the proposed Eagle Mine.

Point-Load Strength Procedure

- The procedure used to determine the equivalent UCS from the point-load test results is based upon a procedure no longer current within the mining industry. The method used is inconsistent with the current standard test methods [2, 3] for determining the point-load strength index of rock. The point-load testing approach that was adopted causes significant uncertainty in the intact rock strength that was determined for each lithological unit.

- Once laboratory UCS testing has been completed, implementation of the current standard point-load test methods are required to interpolate the equivalent UCS from the point-load test results.

Pre-Mining *In Situ* Stress

- The pre-mining *in situ* stress regime has a significant effect on the behavior of underground excavations. The horizontal stresses assumed throughout the stability and subsidence analyses have been underestimated.

- The ratio of the average horizontal stress to the vertical stress is denoted by the letter k. The k ratio assumed throughout the Eagle Mine Geotechnical Study [1, 4] was 2.0. This is based on an equation proposed by Herget [5] to predict horizontal stresses for underground excavations in the Canadian Shield rock units:

$$k = \frac{251.68}{z} + 1.14$$

  where z = depth below surface (m).

- A depth of 300 m was used to determine the k ratio of 2.0. However, near the surface in the area of the crown pillar, Herget's equation predicts significantly higher k ratios. Assuming a depth of 50 m, which better approximates the elevation range expected for the upper stopes for the proposed mine, the predicted k ratio is 6.2.

- A sensitivity study is required to determine crown pillar behavior under a variety of possible horizontal stress conditions.

Crown Pillar Stability Analysis — Scaled Span Analysis

- The Scaled Span concept was developed by Carter [6] as a procedure for empirically dimensioning the geometry of crown pillars over near-surface mined openings, based on precedent and experience.

- Based upon a crown pillar thickness of 57.5 m, which assumes that the 383 m Level is not extracted, and considering a typical RMR_{76} value of 70, the crown pillar is predicted to have a factor of safety of 1.2. Carter [7] suggests that a Scaled Span factor of safety of 1.2 has a very short-term serviceable life (2-5 years) and has an undesirable risk of failure for temporary civil works. He states that such crown pillars pose a high level of concern with regard to a regulatory position on closure.

- Golder [4] states that the Eagle crown pillar is potentially unstable when considering an expected minimum RMR_{76} value of 60, which results in a factor of safety of 0.73. However, Carter [7] suggests that a Scaled Span factor of safety of less than 1.0 has no effective serviceable life and is totally unacceptable with regard to a regulatory position on closure.

- Considering the very low factor of safety achieved with the Scaled Span analysis and Carter's suggestion that even a factor of safety of 1.2 represents a very short-term serviceable life, the possibility of complete crown-pillar failure should be a serious concern. Further detailed analysis using a three-dimensional non-linear modeling code is required to assess the stability of the Eagle crown pillar.

Crown-Pillar Stability Analysis — CPillar Analysis

- The CPillar program [8, 9] can be used to assess the probability of crown-pillar "plug" failure using limit equilibrium analysis. The failure of a plug of rock into the excavation below could occur by shear failure through intact massive rock or by sliding along discontinuities.

- Based upon a crown pillar thickness of 57.5 m, Golder [4] reports that the CPillar analysis indicates that the factor of safety for the crown pillar with RMR_{76} values of 60 and 70 are 3.65 and 6.40, respectively.

- McKinnon et al. [10] conclude that a CPillar analysis represents the simplest design approach for crown pillar stability and results in a high factor of safety. Based upon the empirical database used to develop the Scaled Span analysis, Carter [7] suggests that failure in pure shear is rare.

- Due to the simplified assumptions and limitations of the CPillar analysis technique, the high factor of safety achieved cannot be considered realistic. A rigorous analysis technique that encompasses all of the possible failure mechanisms is required to determine the stability of the crown pillar.

Modeling of Subsidence — Material Properties

- The rock-mass deformation modulus (referred to as the Young's modulus within the Eagle Geotechnical Study) used to simulate the elastic response of the Eagle crown pillar was 56.6

GPa. Derivation of the deformation modulus used throughout the modeling analyses has not been substantiated and is significantly higher than what is predicted with the most commonly used empirical relations [11, 12]. Use of the high deformation modulus will result in lower predicted subsidence displacements, and cause significant uncertainty with the predicted behavior of the Eagle crown pillar.

- Determination of representative rock-mass mechanical properties is a fundamental requirement for input to numerical models of crown pillar subsidence.

Modeling of Subsidence — Modeling Methodology

- The Eagle Project Mining Permit Application states that both plastic and elastic deformations of the crown-pillar rock mass were evaluated. In fact, no analyses were conducted using plasticity theory to predict shear and tensile failure of the rock mass.

- Golder [13] states that linear-elastic analyses were appropriate for the analysis because the major principal stress within the crown pillar region was predicted to be low within the Phase^2 model results. However, the elastic modeling results indicate that tensile failure of the crown pillar is the dominant failure mechanism of the Eagle crown pillar.

- Hutchinson [14] suggests that non-linear (as opposed to linear elastic) or distinct-element modeling codes are required for rigorous analysis of crown pillar stability.

Modeling of Subsidence — Phase^2 Model Results

- The Phase^2 model is not considered to be realistic, as the finite element mesh used to discretize the crown pillar is extremely coarse and severely limits the accuracy of the modeling results. Only one or two three-noded triangle elements have been specified across the thickness of the crown pillar. The default value suggested within the Phase^2 program to ensure accurate modeling results is 10 elements [15].

Modeling of Subsidence — MAP3D Model Results

- Considering the uncertainties with the modeling input parameters and the significant limitations of the elastic analysis, a very low level of confidence should be applied to the predicted subsidence levels of the Eagle crown pillar.

- Rigorous non-linear analysis is required to understand the potential for tensile and shear failure of the crown pillar, while a sensitivity analysis should be conducted to understand the range of expected behavior under all possible geotechnical conditions.

Modeling of Subsidence — Long-Term, Time-Dependant Crown Pillar Behavior

- The long-term, time-dependant behavior of the Eagle crown pillar was not considered as part of the analyses. Carter [7], Carter and Miller [16] and Hutchinson [14] indicate that the time-dependant degradation of surface crown pillars is a serious concern.

- Further investigation and analysis are required to establish the long-term stability of the Eagle crown pillar.

Effect of Discrete Sub-Vertical Fault

- A discrete sub-vertical fault plane that intersects the Eagle deposit has not been considered in any of the stability or subsidence analyses. The potential for shear failure along the sub-vertical fault should be investigated to determine the effect of the fault upon crown pillar stability.

Crown Pillar Hydrologic Stability

- Crown pillar hydrologic stability refers to the integrity of the crown pillar with regard to increases in hydraulic conductivity caused by stress-induced deformation of the crown-pillar rock mass. Mining extraction will produce increasing stress and deformation in the crown pillar as mining progresses upward, reducing the thickness of the crown pillar. As a rock mass deforms, pre-existing joints shear and dilate, while failure of the intact rock blocks form new open fractures. This process causes a significant increase in permeability of the rock mass. Crown-pillar hydrologic stability was not considered in the crown-pillar subsidence analysis or the bedrock hydrogeological investigation.

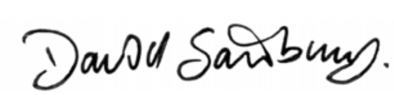
- Golder [17] reports that the hydraulic conductivity of the bedrock units were increased by a factor of three within 15 m of the underground excavations to simulate the damage caused by blasting and relaxation of the rock mass. The increase in hydraulic conductivity caused by blasting and rock mass yielding is generally several orders of magnitude, significantly greater than a factor of three.

- The Society of Mining Engineers (SME) [18] suggests that induced horizontal strain should be less than 0.005 for there to be no significant impacts to surface bodies of water from mining.

- For a preliminary assessment of the crown-pillar hydrologic stability, analysis of the mining-induced strain surrounding the proposed crown pillar, using a three-dimensional non-linear modeling code to determine areas that exceed the SME suggested strain limit is required.

- In 1999, industry best-practice for regional evaluation of crown pillar subsidence and hydrologic stability dictated that a detailed analysis of the mining-induced shear dilation along predominant joint sets be performed. Specifically, an analysis of how the shear dilation relates to changes in joint aperture and changes in hydraulic conductivity was considered relevant. A similar analysis is required to fully understand the crown pillar subsidence and its relationship to hydraulic conductivity at the Eagle Mine.

Submitted by



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