

## Case Study: Thermal Analysis of Artificial Ground Freezing at the McArthur River Uranium Mine

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### Introduction

The McArthur River uranium mine is located in the Athabasca sandstone region in the northern part of the province of Saskatchewan, Canada. It is the world's largest, high-grade uranium deposit with proven and probable reserves of more than 473 million pounds  $U_3O_8$ . It is majority owned and operated by the Cameco Corporation.

This paper presents a case study of the engineering that was carried out in order to artificially freeze the underground ore body at the mine prior to it being mined. Full details of the project

have been previously described by Newman and Maishman (2000). The primary focus of the paper is the application of an advanced thermal analysis tool that greatly simplifies the finite element modeling required during the design and monitoring stages of projects such as that carried out at McArthur River.

### Background

According to Newman and Maishman (2000), the ore body itself is located 550 meters to 620 meters underground where the ground-water pressure is ap-

proximately 5500 kPa. Due to the presence of a hanging wall fault structure, the ore body is surrounded on three sides by fairly dry, competent ground. The other three sides are comprised of highly fractured sandstone with significant amounts of rubble, flowing sand and clay regions. In order to mine the ore, it was necessary to create a frozen wall barrier around the three poor sides of the ore body. The frozen wall barrier was designed to permit drainage of water in the ore and consequently reduce water pressures prior to mining. The wall was also required to provide structural support of weak, clay / ore

ground near to mining cavities. Figure 1 shows a cross-section of the ore body and neighboring geology.

A mechanical freezing system is comprised of a brine cooling and distribution network plus a series of brine freeze pipes installed in the ground to be frozen. Typical ground freezing applications have involved drilling freeze holes from surface or near

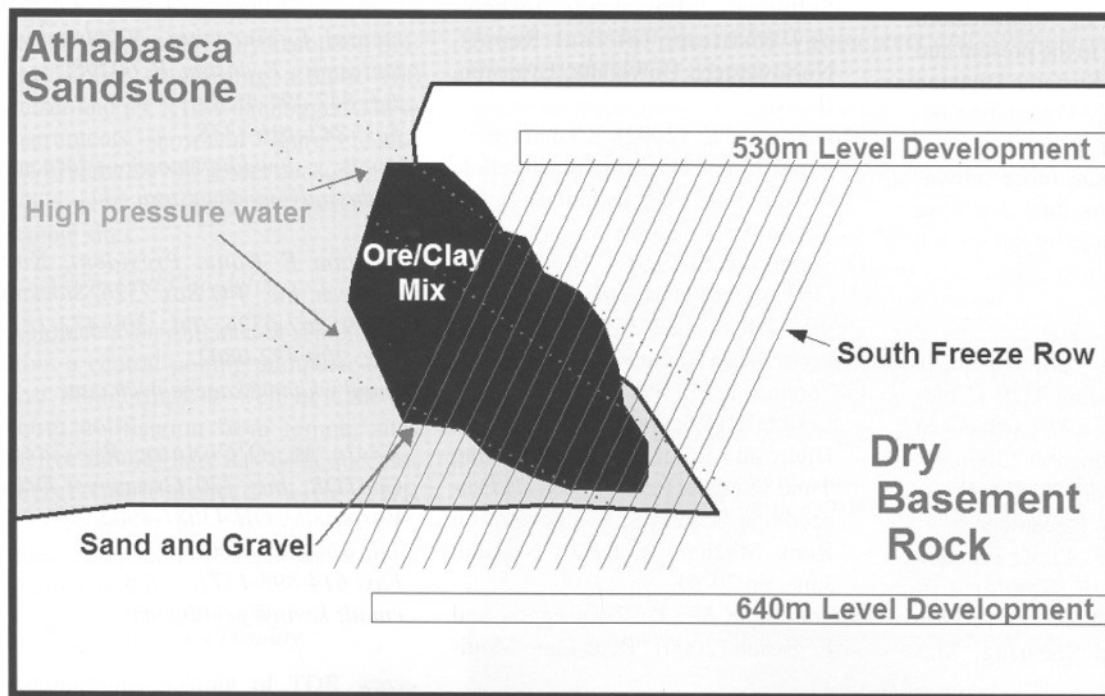


Figure 1. Cross-section of the ore body and neighboring geology (after Newman and Maishman, 2000)

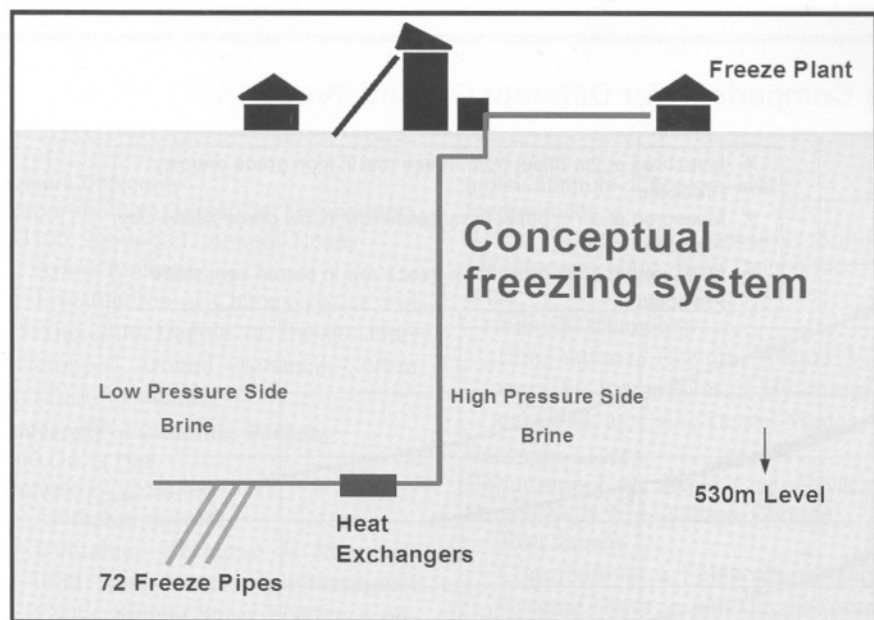


Figure 2. Illustration of the high and low pressure brine distribution networks (after Newman and Maishman, 2000)

surface and these activities have been well documented. In addition, the brine cooling and distribution network has typically included an ammonia compressor with ammonia to brine heat exchangers. The process of installing a "typical" freezing system at McArthur River was made more difficult due to the location of the freeze pipe chamber underground.

The freezing chamber is located 530 meters below ground, which means that the brine pressures within the freeze pipes and associated brine distribution network would equal 5000 kPa if connected directly to the surface refrigeration plant. This is not practical from a design or operations perspective. In order to minimize the brine fluid pressures, the underground brine distribution system was isolated from the surface brine system using shell and tube brine-brine heat exchangers.

The illustration in Figure 2 shows the relative position of the 800 Ton refrigeration capacity freeze plant on surface, the 12" ID brine supply and return lines installed in the shaft, and one of four shell and tube heat exchangers on the 530 m level. The low-pressure brine network on the 530 m level operates within a 150 kPa to 600 kPa pressure range at flow rates ranging between 130

m<sup>3</sup>/hr and 550 m<sup>3</sup>/hr. The design brine temperature was -40 degrees Celsius.

In order to determine the actual growth of the freeze wall it was necessary to install thermocouple strings at several locations around the freezing region. The thermocouples were lowered into a cased hole containing a fine grout mix prior to the grout setting. Each string was comprised of twelve sensors located at five-meter intervals down any given temperature monitoring hole. This enabled the temperature decay to be monitored offset from the freeze pipes in various types of ground (see Figure 1 for comparison of ground types). Ground temperatures were recorded every second day. In this case study, the actual ground temperatures can be used to verify the new thermal analysis numerical tool. This is described below.

**Thermal Modeling and Analysis**

The TEMP/W two-dimensional finite element computer program (GEO-SLOPE, 2002) has been used extensively by many practicing ground freezing consultants for design of artificial ground freezing projects. In the past it was common to apply the thermal boundary condition for a freeze pipe by assuming a fixed temperature decay function for early stages of freezing fol-

lowed by an assumption that the pipe surface is as cold, or nearly as cold as the brine for the remainder of the freezing period.

Recently, TEMP/W has been modified so that the user is able to apply a convective heat transfer analysis for the pipe-ground interface (or any other surface convective heat transfer process). The amount of convective heat transferred between the ground and the chilled brine is dependent on the ground temperature relative to the brine temperature and it subsequently determines what the new ground temperature will be. Based on this approach, the ground will cool at a variable rate and to a minimum value that is determined by the brine flow parameters and the difference between brine and ground temperature.

Convective heat transfer is comprised of two mechanisms: energy transfer due to random molecular motion (diffusion) and energy transfer due to the motion of a fluid (advection/convection). In this case study analysis, we are concerned with convection heat transfer between fluid in motion in a pipe and the pipe wall when they are at different temperatures. Technically, the convective heat transfer is occurring between the internal pipe wall and the fluid but it is acceptable to combine the conductive heat transfer across the steel pipe wall with the convective component to arrive at a combined convective heat transfer coefficient.

Regardless of the nature of the convective heat transfer process, the appropriate rate equation is

$$q = h(T_s - T_f)$$

where q is the unit heat flux (W/m<sup>2</sup>); h is the combined convective heat transfer coefficient (W/m<sup>2</sup>°C); T<sub>s</sub> is the pipe's external surface temperature (°C); and T<sub>f</sub> is the fluid temperature. In the TEMP/W program, the user must input the overall heat transfer coefficient as well as a fixed temperature or time dependent temperature function for the fluid. The physical size of the pipe can also be specified as an option if the actual pipe geometry is omitted from the finite element mesh.

The data in Table 1 summarizes the thermal properties used in the original

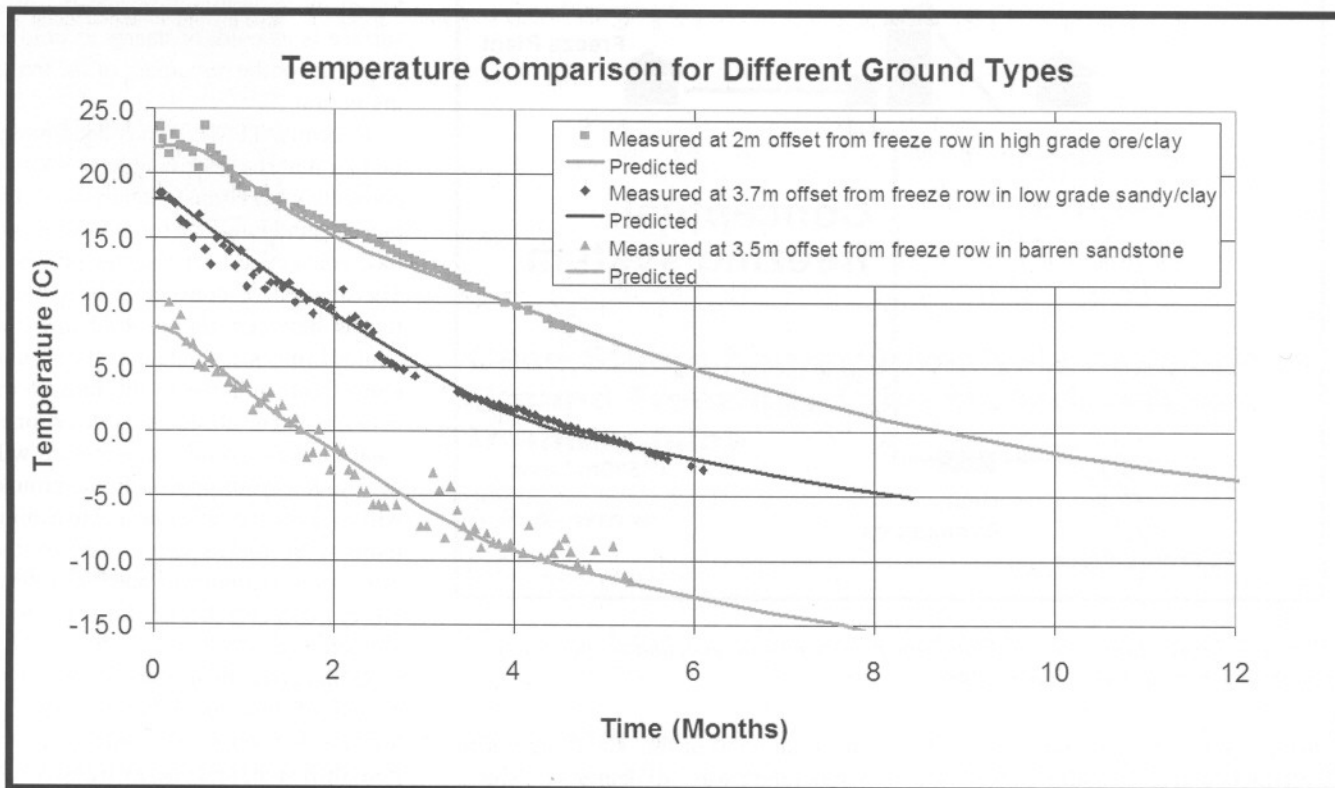


Figure 3. Comparison of computed and predicted ground temperatures for various rock types (measured data after Newman and Maishman, 2000)

thermal modelling (Newman and Maishman, 2000) and in the current analysis.

It should be noted here that no ad-

These results clearly show that the new convective heat transfer boundary condition option can be applied to artificial ground freezing if one knows the brine

finite element analysis, it is now possible to accurately determine heat losses from the soil into the mechanical freezing system without having to make an assumption about the appropriate temperature boundary condition to use in the analysis.

Table 1. Thermal Properties Used in Analyses

	Conductivity (W/ m °C)	Bulk Volumetric Water Content (%)
Silicified Sandstone	5.2	10
Clay / Ore	1.2	50
Basement Quartzite	5.6	2

justments to the freeze pipe boundary condition temperatures were made in the model when calibrating the thermal conductivity of the clay / ore ground. The actual freeze pipe temperature was computed as a result of the convective heat being removed by the brine.

Figure 3 is a comparison of computed and measured ground temperatures for three of the main rock types and initial in-situ ground temperatures.

fluid temperature and freeze pipe diameter. The overall convective heat transfer coefficient can readily be computed based on the brine flow rate and other hydraulic flow properties.

**Conclusions**

Artificial ground freezing of the high grade McArthur River uranium ore deposit was carried out under extreme conditions. Due to advances in thermal

**References**

Geo-Slope, 2002. TEMP/W Version 5 Users Manual, Geo-Slope International Ltd., Calgary, Canada.  
 Newman, Greg and Derek Maishman. Artificial Ground Freezing of the McArthur River Uranium Ore Deposit. Proceedings: International Conference on Ground Freezing and Frost Action in Soils. Belgium. September, 2000.

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