Artificial Ground Freezing: An Environmental Best Practice at Cameco's Uranium Mining Operations in Northern Saskatchewan, Canada

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Abstract Cameco Corporation (Cameco) is becoming a leader in the application of artificial ground freezing for controlling water and ground stabilization at its existing and in-development high-grade uranium mines in Canada. Artificial ground freezing (AGF) has been used in the mining industry over the past 125 years for support of shaft sinking, tunneling, and foundation excavation. The AGF process involves chilling a brine solution to between -25 °C and -35 °C in a large, conventional refrigeration plant. The brine is then circulated through the ground within steel pipes in a linear or grid pattern to remove heat from the ground and freeze water within the soil/rock pore spaces to improve soil strength and decrease the mobility of liquid water. Traditional AGF projects are usually short-term in nature, which has limited the relevance of the long-term efficiency and environmental benefits of the process. Freezing projects at the northern Saskatchewan uranium mine sites typically will be active for 10 years or longer, providing an opportunity to consider the development of a best-practice philosophy for all phases of the project, from design through to operations and decommissioning of freeze systems.

Key Words artificial ground freezing, water control, shaft sinking, tunnelling

Introduction

Cameco strives to continuously improve environmental performance in all aspects of operations. Main areas of focus have been waste reduction, improved air quality, reduced energy consumption, and decreased water intake and treated water release volumes. Ground freezing has been recognized as a critical component of Cameco's mining success: creating a barrier to groundwater flow, strengthening weak ground mass, and providing control of radon gas release. This paper will focus on the environmental management benefits that can be gained through the implementation of ground-freezing technology at uranium mining operations in northern Saskatchewan. Most notably, the use of long-term ground-freezing technology provides ongoing groundwater inflow management thereby substantially reducing treatment and release volumes. In addition, operating procedures and practices to reduce energy consumption has been developed and has explored the potential for heat-recovery systems as part of freeze-plant operations which can be applied to other operational areas, decreasing energy demands. Other innovative uses for freezing are being investigated in support of future shaft sinking which could also further enhance the environmental benefits of this technology.

How Ground Freezing Works

Artificial ground freezing (AGF) is a process by which stored thermal energy (e.g. heat) is removed from soil or rock to such an extent that the water held in the interstitial pores in the ground cools to below the phase change temperature and turns to ice. When a cold heat sink (i.e. cold brine pipe) is introduced in the ground, stored thermal energy flows from the ground toward the heat sink and the temperature of the ground drops. The warmer brine then flows back to the refrigeration plant where it is re-cooled and circulated back through the system. The rate of ground cooling is dependent on several things: the thermal conductivity or ability of the ground to transport heat, the temperature of the ground and the brine, the ability of the ground to release heat (e.g. heat capacity), the magnitude of the heat gradient established between the warm ground and the introduced cold heat sink, and finally the amount of water stored in the ground (Newman 1997). The amount of water is important because when water changes phase from liquid to solid, it releases latent heat which must also be removed from the system through the cold heat sink.

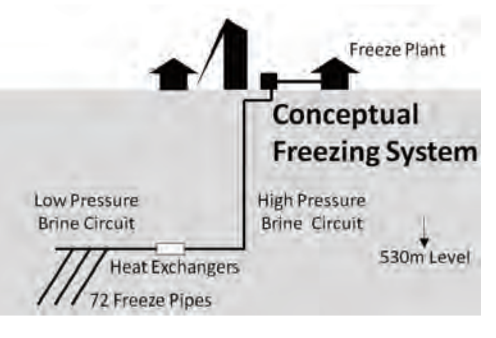

***Figure 1** Typical underground ore freezing concept.*

A typical ground freezing system is shown in Figure 1 (Newman 2000). In this image a series of freeze pipes have been installed in a linear pattern to optimize the rate of cooling and create a frozen barrier wall. A freeze pipe is a two-part system that consists of an outer steel casing with a sealed bottom cap and an inner high-density polyethylene tube. Cold brine, typically calcium chloride ($CaCl_2$) chilled to between -25 °C and -35 °C, is introduced inside the polyethylene tube where it flows to the end of the freeze pipe before returning to the top of the hole in the annular gap between the tube and the outer steel casing. It is during the return flow to the top of the freeze pipe that the cold brine draws heat from the surrounding ground.

Ground freezing requires front-end design and analysis to determine the rate of freezing, the optimum freeze-pipe configuration, and the size of refrigeration or freeze plant necessary to accomplish the project goals. Finite element analysis (FEA) is used to develop a design and to size the freeze plant so it can be procured and so that power consumption rates can be known ahead of time. A typical ground-freezing heat-load curve is shown in Figure 2. In this figure the units of heat extraction are kilowatts per meter (kW/m) which is an energy value per unit time per unit length of freeze pipe. It is quite typical to have many thousands of meters of installed freeze pipes surrounding a mining area and so it is not uncommon to need several megawatts of electrical power available to drive the system. Obviously any opportunity to reduce this energy requirement, or to recover the waste heat energy, is a good practice to adopt.

Why Ground Freezing is Needed in Uranium Mines

The high-grade ore deposits at Cameco's McArthur River and Cigar Lake uranium mines are located between 450 and 600 m below ground surface at an unconformity between highly fractured silicified sandstone above and relative dry granitic basement rock below. The fractured sandstone contains water in a fracture network connected to ground surface and as such the water pressure at the depth of the ore zones is as high as 6000 kPa and has unlimited flow potential. In the vicinity of the orebodies themselves, the ground is often de-silicified with potentially flowing sand and unconfined squeezing clay. To complicate matters, the pore-water in the ore zone vicinity contains high concentrations of radon gas which comes out of solution as soon as the pore water is depressurized (e.g. enters the mine workings below) (Werniak 1999). A typical cross-section of the geology and associated mining-related hazards is given in Figure 3. This particular image is representative of the conditions at the high-grade McArthur River mine located in northern Saskatchewan, Canada.

During early design phases at McArthur River there was discussion about the potential for using a combination of cement grouting and pumping to stabilize the ore zone and control the pore water. Cement grouting will work in circumstances where the ground or rock formations are susceptible to grout penetration. This would be the case in the fractured sandstone, but the highly altered ground directly adjacent to the ore zones proved to be too variable and the risks associated with trying to grout the zone were deemed too high. Likewise, allowing inflow and having sufficient pumping capacity to remove the water carries very high uncertainty. In addition, allowing the high radon-bearing water to flow intentionally into the mine poses an unnecessary risk to mine workers. Finally, if very high inflow volumes were allowed, large amounts of water would have to be pumped to surface and treated prior to release to the environment – a load which could exceed 3000 m^3/hr. For these reasons grouting and

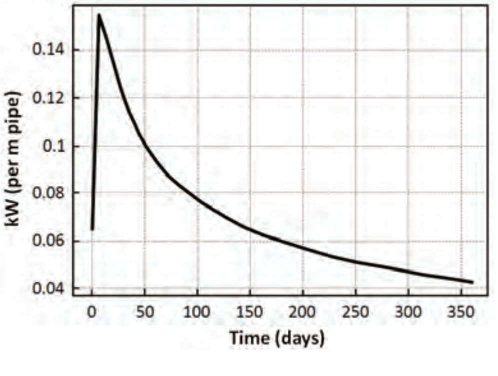

Figure 2 *Typical power consumption curve per meter of installed freeze pipe.*

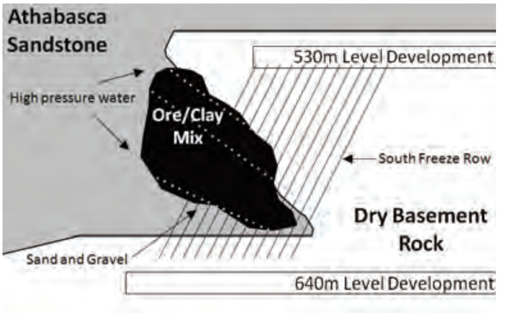

Figure 3 *Cross-section of ore and original freeze wall concept at McArthur River Mine.*

pumping water were deemed to be a non-viable primary control strategy and ground freezing was considered not only the most feasible operational solution, but also is beneficial in that it reduces a significant volume of water which would require management.

Several implications of the challenging ground conditions are evident in Figure 3 as they relate to ground freezing. First of all, given the high-pressure water and the poor ground conditions in the vicinity of the ore, it is not possible to mine the ore without depressurizing the water and stabilizing the ground, both achieved by ground freezing. Once the ground is frozen, or alternately a frozen barrier wall is developed to surround the ore, the encapsulated ore zone can be de-pressurized in preparation for mining. At McArthur River the ore zone is located along an up-thrust fault with dry ground both above and below the ore. This is advantageous as there are two natural "dry" sides to a virtual box around the ore. The access on two dry sides means only four freeze walls need to be created to complete the "box" effect to isolate the ore zone as shown in Figure 4.

The above discussion focuses on ground freezing in support of mining production, however there are also challenges that have arisen in sinking the mine shafts that can be addressed in a unique way with ground freezing. McArthur River's three mine shafts were sunk using conventional grouting to create a "dry ground cover" below the advancing shaft excavation. The process was long and not without risk. At the Cigar Lake mine, the first shaft was sunk conventionally as was the start of the #2 shaft. However, during sinking of #2 shaft at a depth of 390 m, a high inflow zone was intersected during the grouting operation and control of the grout well was lost which resulted in the entire shaft flooding (Beattie 2008).

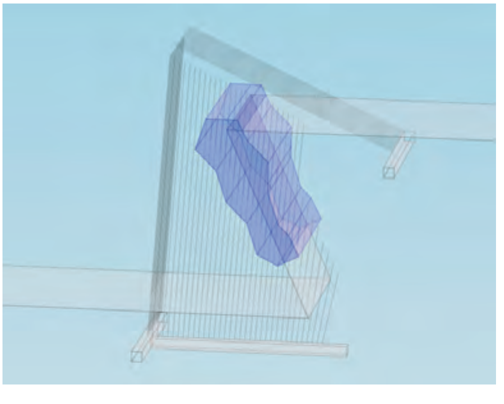

Figure 4 Current freeze wall at McArthur River showing a cathedral ceiling "box" around ore zones.

The subsequent delay to mine development, as well as the water pumping and treating required to remediate the shaft, has proven costly. Cameco has applied the knowledge gained from this experience. In the future, mine shafts will be sunk using a unique combination of freeze-wall barrier with thawed central core, instead of a grout-curtain approach. More details of this best-practice approach to using freezing in support of shaft sinking are provided in the following section.

Best Practices for Implementing AGF

The process of AGF is clearly demonstrated as a critical operational need at the high-grade McArthur River and Cigar Lake mines. This section presents in more detail how ground freezing has been implemented with environmental stewardship and safety in mind. As previously mentioned, typical ground-freezing projects for civil construction works have durations of several weeks to several months depending on excavation time through the frozen ground and installation of the tunnel liner or foundation. In the current study cases, the ground freezing must remain active for 10 years or longer, which in turn, creates different and additional challenges while also providing unique opportunities to identify areas of the AGF process that can be optimized in terms of environmental and safety performance.

Water Management

One of the key environmental gains is that AGF offers benefits in terms of water management. AGF provides a means of groundwater control by "exclusion", eliminating the need for dewatering (Bell 1993). Dewatering would require pumping and rerouting groundwater into a circuit which would involve a treatment facility and subsequent release to a receiving environment. In addition, water treatment would result in a waste stream that would have to be contended with separately. Utilizing AGF offers protection to nearby water bodies and leaves the groundwater table unaffected.

Pumping and treating water as a method of control results in an unnecessary continuous release to the environment and additional costs to construct and operate pumping, treatment and release systems.

Permanent Shaft Freezing

Currently the three mine shafts at McArthur River introduce 240 m^3/hr of water into the mine which must be pumped to surface, treated, and released to the environment. While it is not possible to easily remediate these shafts using ground freezing, it is possible to use ground freezing on future shafts to not only facilitate safer shaft sinking relative to grouting but to permanently seal the shaft against any water inflow during mine operations.

Current planning for shaft sinking at two mines calls for ground freezing to remain active during shaft operations. There is some risk associated with this in that if the freeze zone around the shaft grows inwards and intersects the shaft liner face, any humidity in the shaft will freeze and build up as an ice layer on the shaft wall. If this ice were to slough off it could be a significant hazard to equipment and people in the shaft. As such, it is unacceptable to allow ice to build up on the shaft wall in a permanent freeze scenario. In order to avoid this possibility, engineers are planning to recover the rejected heat from the freeze plant which is typically lost to the atmosphere in the refrigeration process. The previously "rejected heat" can instead be added to the ground adjacent to the shaft concrete liner such that the frozen zone protecting the shaft from water inflow is not able to grow inwards to touch the shaft liner and potentially develop an ice hazard. An example of this concept is shown in Figure 5. Here, in this steady-state finite-element analysis solution, the freeze front has become stationary at a distance about 3 m outside the shaft wall and the shaft wall is a constant temperature of about 5 °C. The technology to achieve this heat re-injection is readily available and is cost effective to apply while giving active control over the shaft wall temperature. While some added electrical costs will be necessary to run the system, there should be zero inflow into the shaft and minimal risk to shaft equipment or people from falling ice.

Heat Recovery to Pre-heat Mine Air

While the previous section discusses using rejected freeze-plant heat for shaft lining protection against freezing, the other freeze plants on site that are used to freeze the underground orebody can also be harnessed for their excess heat. It is relatively simple to transfer the heat from the hot, compressed ammonia to a separate glycol system instead of releasing it to atmosphere. The heat contained in the glycol system can be used in various ways including:

- Pre-heating mine ventilation air to reduce the amount of burned propane and in turn reducing the greenhouse gas emissions (less propane use also means less transport of propane to site using tanker trucks further reducing carbon loading to the environment);
- Heating mine surface structures such as offices and drys; and
- Heating water for showers and other processes.

The amount of recoverable heat is in the order of 1 megawatt per 300 tonnes refrigeration and Cameco will ultimately have over 5000 tonnes refrigeration combined across its mines in Northern Saskatchewan alone.

Power Consumption

The uranium mines are located in northern Saskatchewan and in the summer months there are frequent lightning strikes that temporarily shut down the provincial power distribution network. All mines have backup diesel power generation capability, but the freeze plants are not intentionally operated on this back-up power during outages. The ground freezing is closely monitored via a network of temperature sensors that indicate the extents of the frozen ground and the temperature gradients across the freeze zones. Knowledge of the ground conditions at all times provides confidence to leave the freeze plants off during power outages which saves costs and greatly reduces the carbon footprint should diesel power be used to run the multi-megawatt freeze-plant motors.

Surface Drilling and Brine Isolation

More recently, at Cigar Lake, freeze hole drilling has been done from surface instead of from underground. This approach is deemed to reduce the underground risk as there is no chance of introducing minewater into the open mine workings below. It also has the potential downside that the freeze holes are now 460 m long instead of 80 m long which requires over five times the heat load and energy consumption to run the freeze plant. To offset this downside, a technique has been developed whereby the brine pipes installed inside the freeze hole are capable of isolating the active freezing portion of the pipe to the desired bottom 80 m of the hole instead of the entire hole. The brine isolation system is cost effective to install and will save millions of dollars annually in operating costs in terms of power consumption. In addition, the near-surface soil horizons will not be frozen and there will be no interruption to local groundwater flow patterns.

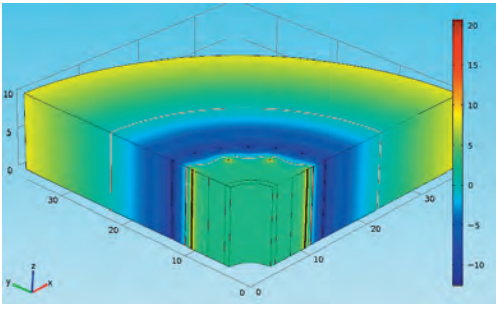

__Figure 5__ Heating pipes installed to prevent freezing from reaching shaft liner (dark zones are ice).

Summary
Artificial ground freezing is used as a best-practise method for water control and stability control uranium mines in northern Saskatchewan. The use of large ground freezing systems over long terms affords the opportunity to consider a "best practice" philosophy when it comes to designing and operating these systems. These best practice approaches adopted by Cameco have a direct impact on worker safety in terms of radiation exposure, minimizing water inflow into mine workings related to both ore extraction and shaft sinking and operations, and harnessing the otherwise rejected heat from the freeze plants for other necessary site operations which results in less carbon-derived energy consumption.

While Cameco has been actively freezing orebodies for over 15 years, the company continually strives to identify new opportunities to apply ground-freezing technology to minimize the impacts of collecting, treating, and releasing water, and for harnessing heat energy that would otherwise be released to atmosphere.

Acknowledgements
The authors thank the IMWA 2011 Congress committee for the opportunity to bring this important topic to the attention of a wider audience.

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