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# EXTRACTING COLD ENERGY FROM BACK-FILLED ZONES TO PRE-FREEZE NEW MINING ZONES IN CANADIAN URANIUM MINES: NUMERICAL MODELING AND EXPERIMENTAL VALIDATION

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***Abstract—*** Athabasca basin in northern Saskatchewan is the home to high-grade uranium ores – known as the Saudi Arabia of the uranium world. McArthur River and Cigar Lake mines are two underground mines located in the Athabasca basin in northern Saskatchewan. Due to high uranium content and weak ground structure, the uranium ore is extracted using special mining techniques, namely raise boring in McArthur River and jet boring in Cigar Lake mine, in which the ground/orebodies need to be frozen before it is excavated. The artificial ground freezing (AGF) system employs a refrigeration plant to produce brine (calcium chloride) at -30°C to freeze the ground by pumping it to the coaxial/bayonet tube heat exchangers installed in the drill holes. As the mine progresses, orebody in the old zones depletes, and new zones need to be developed. The depleted zone typically had been frozen for several years, for which ground temperature reaches close to brine temperature. This paper explores a novel idea of extracting "coolth" energy from the depleted zones to pre-freeze new zones. This could potentially shorten the overall freezing time in the new zone and reduce overall energy consumption and its associated carbon footprint. The concept is tested using a laboratory-scale AGF facility at McGill University. A mathematical model is also developed and validated against experimental data. The model is then used to simulate mine field conditions. The results suggest that the pre-freezing technique can shorten the total freezing time from 9 to 7 months with potential energy savings of up to 37%. Future work will focus on design improvement, techno-economic analysis, and possible implementation.

***Keywords:*** artificial ground freezing; freeze pipe; pre-freezing; underground mining; energy extraction

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## I INTRODUCTION

First application of artificial ground-freezing (AGF) techniques can be dated back to 1862, when Siebe Gorman & Co developed the first AGF device to resolve shaft sinking issue at a coal mine; inspired by ground freezing phenomenon in Arctic regions [1, 2]. Since then AGF techniques has been used in several technological variations to assist practical challenges in the field of civil engineering, mining industry, environmental impact mitigation and other projects. Devices such as bayonet tubes/freeze pipes [3] and two-phase-closed-thermosyphones (TPCT) [4, 5] in combination with different sources of heat sinks [1, 6], have been extensively studied and implemented for ground freezing and energy extraction [7–9]applications. In the mining industry, especially in some uranium mines, ore mining involves freezing the ore and its surrounding rock prior to mining; due to prevailing unfavourable ground conditions. McArthur River mine and Cigar Lake mine, located in Northern Saskatchewan, are two examples of such uranium mines. In McArthur River mine, the ore is mined using *raise boring* technique and the water flow around the ore body is prevented by *grouting and artificial ground freezing* [10]. In Cigar Lake mine, the ore body and the surrounding rock is artificially frozen prior to extraction of ore using *high pressure water jet* [11]. Both of these mines are operated by Cameco Corporation [10, 11] and utilize freeze pipes in a closed-loop arrangement for ground freezing [1].

In Cigar Lake Mine and McArthur river mine, the ore body is divided into several zones. These zones are mined sequentially as they are scattered in the mine due to geological factors. The AGF system at these mines is comprised of coaxial freeze pipes/bayonet tubes that are drilled from the surface to the target ore body. Freeze pipes are connected to refrigeration plants in a closed-loop arrangement. Cold brine at sub-zero temperature is supplied from a refrigeration plant that is located on the surface. The brine ideally enters from the axis of the inner coaxial tube and exits from the peripheral flow path that is defined by the outer surface of the inner tube and inner surface of the casing [3]. Throughout the ore mining operation, the mining zone stays frozen and resulting cavities are back-filled [11].

When ore mining is completed at an initial zone, there is an excess of cold energy that can be potentially used somewhere at the mine. One idea is to use the excess of cold energy from the initial zone to pre-freeze the upcoming zone that is next in the mining sequence. Once the pre-freezing is complete, achieving the required frozen ground temperature in the pre-frozen zone would require less energy compared to the energy required if pre-freezing activity is not performed.

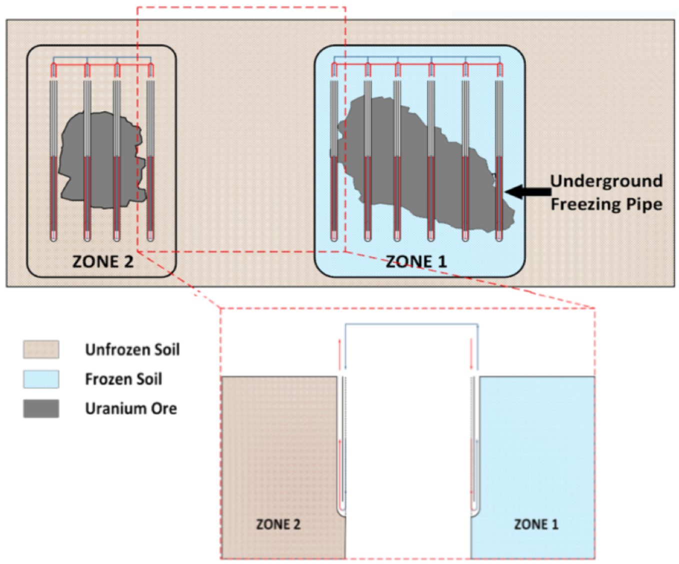


Figure 1. Schematic illustration of pre-freezing process

In the pre-freezing process illustrated in Fig.1, brine at ambient temperature is pumped in the excess-cold-energy-Zone-1. While passing through Zone 1, the brine releases energy and exits the freeze pipe at lower temperature. This low temperature brine is then pumped to the target; Zone 2. While passing through Zone 2, the low temperature brine absorbs energy and pre-freezes the Zone 2. This process continues till Zone 1 and Zone 2 are in thermal equilibrium, over time. An added benefit of potentially impelementing this idea at Canadian Uranium mines is that significant additional Capital Expenditure (CAPEX) would not be required. This is because the same freeze pipes that are required to freeze the new zone will be used.

In this paper we have studied this schematically illustrated pre-freezing process. To the best of authors' knowledge, research work to study the extraction of cold energy from back-filled mining zones and using it to pre-freeze a new mining zone, has not been conducted. This paper aims to bridge this research gap by evaluating the idea technically; using a mathematical model that is validated with experimental study. First, the Experimental setup will be described in Section II followed by mathematical model in Section III. Then, the results and discussion will be presented in Section IV, that will be followed by conclusion of the study in Section V.

## II Experimental Setup

Simplified flow chart of the experimental model is depicted in Fig. 2. The laboratory setup consists of two freeze pipes, located 3 cm apart, in fully-saturated ground (sand). Bulk thermo-physical properties of the sand that were mixture specific, were determined experimentally while specific heat is taken from the work of Harris [2, 12]. Heat flux to the ground can be controlled through a heater that encloses the ground. The experimental setup is insulated. Pre-freezing process is simulated by supplying 57% diluted Ethylene Glycol solution coming from the chiller. The chiller can supply chilled liquids up to -30 °C using a positive displacement pump that is controlled by variable frequency drive. Over 80 thermocouples are installed throughout the setup to measure temperatures at various locations over time; for ground, wall and flowing fluid. Data is captured using a data acquisition system. LabVIEW program developed in the lab controls flow rates and the heater and records measurements from flow meter and thermocouples. Detailed description of the experimental setup can be taken from study by Alzoubi et al. [13].

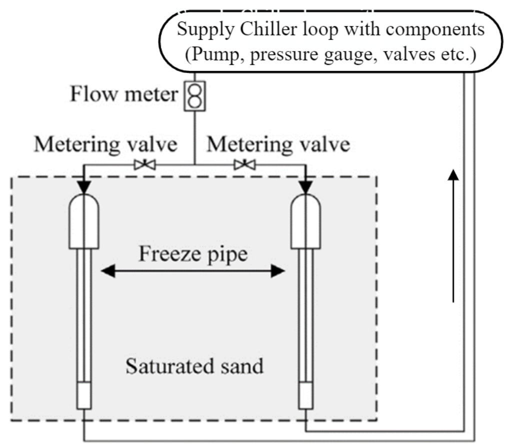


Figure 2. Simplified flow chart of experimental model

## III Mathematical Model

### A Geometric Model

Geometric model that was used to simulate the pre-freezing process is presented in Fig. 3. Liquid refrigerant enters Zone 1, having excess of cold energy, from the outer periphery of the freeze pipe. The liquid releases the surplus energy to Zone 1 and exits via the inner tube. The refrigerated liquid then enters the Zone 2, that is to be pre-frozen, from the inner tube of the freeze pipe. While passing through the outer periphery, the refrigerant absorbs heat and pre-freezes Zone 2 before entering Zone 1 again in a cycle.

### B Governing Equations and Boundary Conditions

Mathematical model of the ground freezing simulation involves solution of the equations of conservation of mass, momentum and energy in the computational domain using Control Volume Finite Difference Method (CVFDM) techniques. There are two important domains to consider for formulating a mathematical model: (1) Coolant flow in

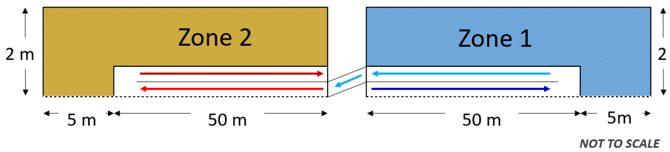


Figure 3. Pre-Freezing geometric model for CVFDM Simulation

the freeze pipe (2) Porous ground structure surrounding the freeze pipe. The coolant-flow model is adopted from the work done by Alzoubi et al. [3, 13]. In the mathematical model, the domain is thermally coupled at the freeze-pipe-wall. On the ground-side, *local thermal equilibrium (LTE) hypothesis* [13, 14] is applied to solve the energy conservation equation. LTE hypothesis assumes that the temperature difference between the pores in the ground and the sand particles is negligible. LTE assumption is valid under certain conditions of length and time scale as described by Alzoubi et al. [13].

Mathematical model is presented below:
— Conservation of mass:

$$\frac{\partial}{\partial t}\rho_\ell + \nabla\cdot(\rho_\ell \mathbf{u}) = 0 \tag{1}$$

— Conservation of momentum:

$$\frac{1}{\varepsilon}\frac{\partial}{\partial t}(\rho_\ell \mathbf{u}) + \frac{1}{\varepsilon^2}\nabla\cdot(\rho_\ell \mathbf{u}\mathbf{u}) = -\nabla P + \frac{1}{\varepsilon}\nabla\cdot(\mu_\ell \nabla \mathbf{u}) - \underbrace{\frac{\mu_\ell}{K}\mathbf{u}}_{S_D} - \underbrace{\frac{C_E}{K^{\frac{1}{2}}}\rho_\ell\,|\mathbf{u}|\,\mathbf{u}}_{S_E} - \underbrace{\mathbf{u}C_m\frac{(1-\gamma)^2}{\gamma^3}}_{S_m} \tag{2}$$

where $C_m$ and $C_E$ are the mushy constant and ergun coefficient respectively. $S_D$, $S_E$ and $S_m$ are the source terms for darcy, inertial and mushy influences. Total resistance to the flow field is modeled by $S_D$ and $S_E$. However, reduction of velocity $\mathbf{u}$ within the mushy region (boundary of the frozen ground) is model using the source term $S_m$. Reducing the velocity $\mathbf{u}$ is required in the area where the ground water is gradually pre-frozen to ice.
— Conservation of energy:

$$\frac{\partial}{\partial t}\left[\varepsilon(\gamma\rho_\ell h_\ell + (1-\gamma)\rho_s h_s) + (1-\varepsilon)\rho_p h_p\right] + \nabla\cdot(\rho_\ell h_\ell \mathbf{u}) = \nabla\cdot(k_e\nabla T) - \underbrace{\nabla H\left[\left(\varepsilon\rho_\ell\frac{\partial\gamma}{\partial t}\right) + (\nabla\cdot[\rho_\ell \mathbf{u}\gamma])\right]}_{S_H} \tag{3}$$

$k_e$ is the effective thermal conductivity and is given by:

$$k_e = \varepsilon\gamma k_\ell + (1-\gamma)\varepsilon k_s + (1-\varepsilon)k_p \tag{4}$$

$S_H$ is a source term that models the latent heat of fusion $\nabla H$ that is involved in the pre-freezing process.In the equations given above, the subscripts $p$, $s$ and $\ell$ represent the sand particles, solid water and liquid water that constitute the porous ground surrounding the freeze pipe.

Boundary condition applied to the geometric model for CVFDM solution to the mathematical model described in Section B, are provided below:
*Freeze pipe*—**Inlet**: $\dot{m} = \dot{m}_{in}, T = T_{in}$ **Outlet**: $P = P_{out}$ , $\mathbf{n}\cdot\nabla T = 0$ **Outer Wall**: $T = T_{wall}, \mathbf{u} = 0$.
*Ground* — Modeled as 2D axis-symmetric ; Freeze-pipe's outer wall is thermally coupled with ground; there is zero heat flux at the far boundary of the ground's computational domain. Simulation boundary conditions are reported in Section IV.

### C Numerical Simulations

Software package utilized to perform the CVFDM numerical simulations was ANSYS version 16.1. Mesh independent study was conducted prior to the application of LTH hypothesis. The study was performed beginning at $5x10^3$ number of elements. The mesh was successively refined till a difference of 1% in the results was achieved. Mesh size of $6.3x10^5$ elements presented a reasonable mesh size with balanced computational time and reasonable accuracy. Thus, this mesh size was selected for simulations. The CVFDM model was solved using SIMPLE algorithm applying second-order upwind discretization scheme for energy, momentum and pressure equations of the transient model. Residuals were limited to the value of $10^{-6}$. User defined function (UDF) code in was designed in the software package ANSYS 16.1, to specify the inlet velocity, inlet temperature, and properties of water that are temperature-dependent.

## IV Results and Discussion

This study aims to validate the idea of using excess energy from the already mined zones to pre-freeze the zones that are next in the mining sequence. Using the model described in Section III, CVFDM simulations of the pre-freezing process along with experimental study was conducted to validate the potential of the idea. In this section we will: 1) Provide a closely matching comparison of the mathematical model and the experimental results to validate the model, and 2) Results of the numerical solution to the model to study the pre-freezing idea.

First the numerical model was validated using the experimental setup described in section II. Same operational conditions were simulated in the experiment and the computational model. The temperature data over time recorded by the thermocouples, installed at various locations (labeled in fig. 5) of the experimental setup, were compared with the temperature outputs of the simulation. The exact location of the thermocouples in the experimental study can be found in the work done by Alzoubi et al. [13]. From Fig. 4, it can be observed that the experimental and simulation results of the inlet and outlet temperatures of the freeze pipe for both zones match closely. From Fig. 5 it can be observed that the ground temperatures at the same locations in the experiment and numerical simulations also match closely. Mathematical model, formulated in Section B, is thus validated with the experimental results due to the displayed proximity of the data captured in both. The mathematical model validated in this comparative analysis was used to perform the simulation study.

The simulation was performed in two stages. In Stage 1, both Zones were thermally de-coupled while Zone 1 was frozen for 9 months; simulating the not-pre-frozen-ground OR ground freezing process at Zone 1 to store excess energy. When temperature of -25 °C was

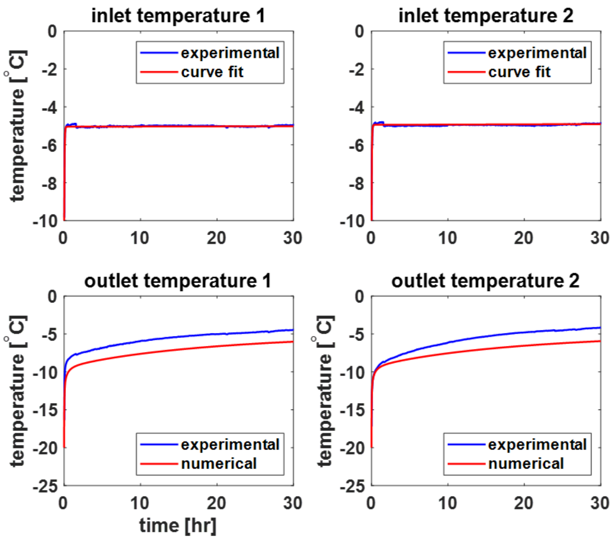


Figure 4. Inlet and Outlet temperatures of freeze pipes installed at Zone 1 and Zone 2: Comparison of experimental and numerical results

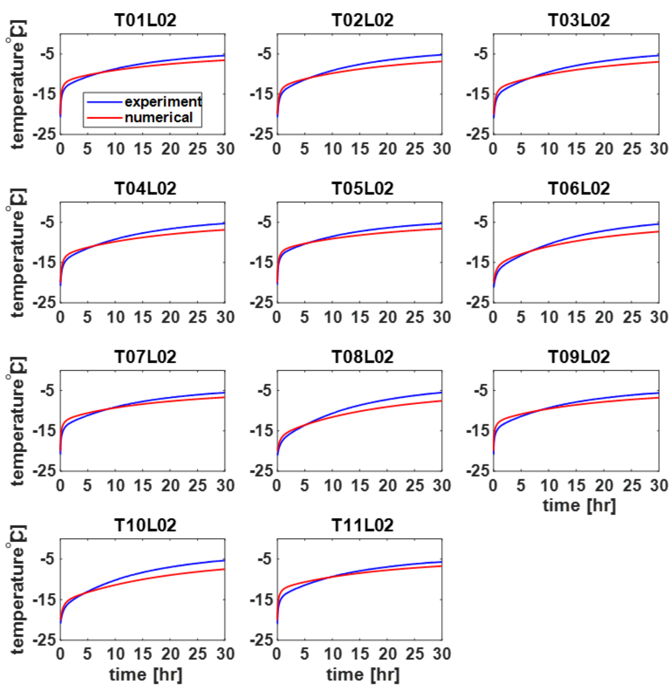


Figure 5. Comparison of temperature recorded by thermocouples vs. temperature solved by numerical solution to the mathematical model at various locations

achieved in Zone 1, it was thermally coupled with Zone 1 to start the pre-freezing process in Stage 2. The cold energy stored in Zone 1 was transferred to Zone 2 till thermal equilibrium was achieved. Simulation results of average volumetric temperatures of Zone 1 and Zone 2 along with the energy transferred between the two zones in both stages is reported in Fig. 6 and Fig. 7.

Transient simulations were performed for a reasonable time period and the results reported in fig. 6, fig. 7 and 8 are truncated to a meaningful representation of time. The 2D model was also translated to a 3D model with same boundary conditions. Simulations were then performed and similar results for power consumption were obtained as reported in Fig. 8.

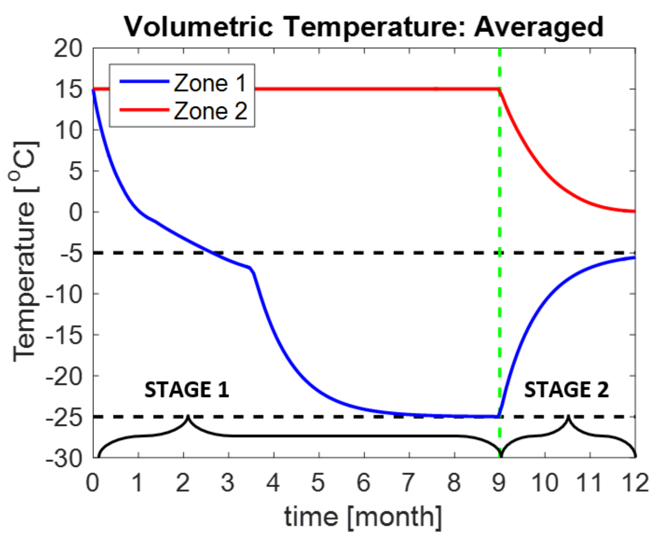


Figure 6. Volume averaged temperature profiles of Zone-1 and Zone-2 in stages

3D simulation model was used to compare the energy (per unit volume, per unit length) required to freeze the pre-frozen Zone 2 with the energy required to freeze the not-pre-frozen Zone 1. The results are presented in the Figure 9.

It is to be noted that the energy extracted from Zone 1 to pre-freeze the Zone 2 to 0°C is 37 kWh/$m^3$/m. After pre-freezing, the energy required to freeze the Zone 2 is 63 kWh/$m^3$/m over 7-month time period. Thus, 37% of the energy is expected to be saved if the upcoming zone in the mining sequence is pre-frozen using the excess cold energy of the already mined zone. Such energy reductions are expected to improve the carbon footprint of the energy intensive mining operation. Furthermore, if the design of freeze pipes can be further improved, additional energy saving benefits can be achieved over the lifespan of the mine. It is also interesting to note from figure 9 that the time taken to freeze the not-pre-frozen ground is 9 months. However, a reduction of 2 months (22%) in the freezing time is achieved if the pre-freezing operation is performed on the zone. Such significant reduction in freezing time is also beneficial for the overall mining operation.

A *limitation* of this study is that the energy required to pump the

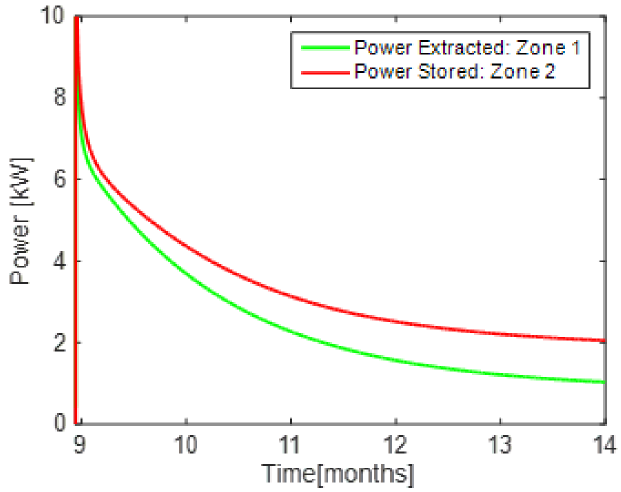


Figure 7. Comparison of cold energy stored in Zone 1 vs. cold energy extracted by Zone 2 over time

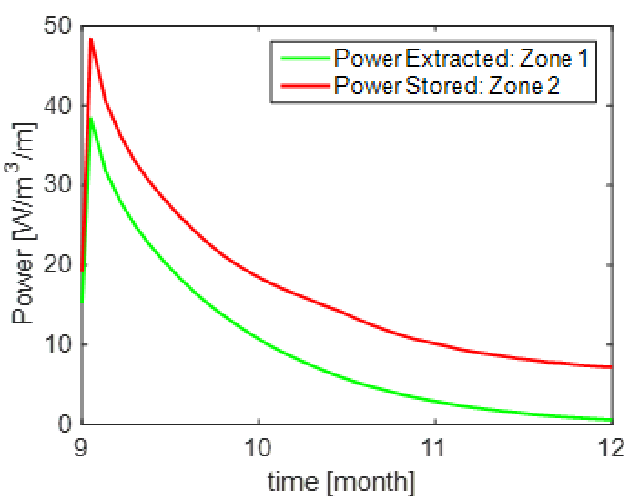


Figure 8. 3D simulation: Comparison of cold energy stored in Zone 1 vs. cold energy extracted by Zone 2 over time

refrigerant from the back-filled zone to the new zone to be frozen is ignored. The two zones can be very close or far apart. Thus, it is to be assumed in the interpretation of these results that both zones are in close proximity and energy consumed to pump the refrigerant between the zones is negligible. Freeze-pipes have to be installed regardless of the decision of a mine to pre-freeze a zone. Thus, the only additional cost (Energy/CAPEX) of pre-freezing a zone would be the transport mechanism of the refrigerant between the two zones; comprising of pumps, pipes and fitting etc. However, the distance between the two zones will affect the technical and economic feasibility of the idea for a particular mine.

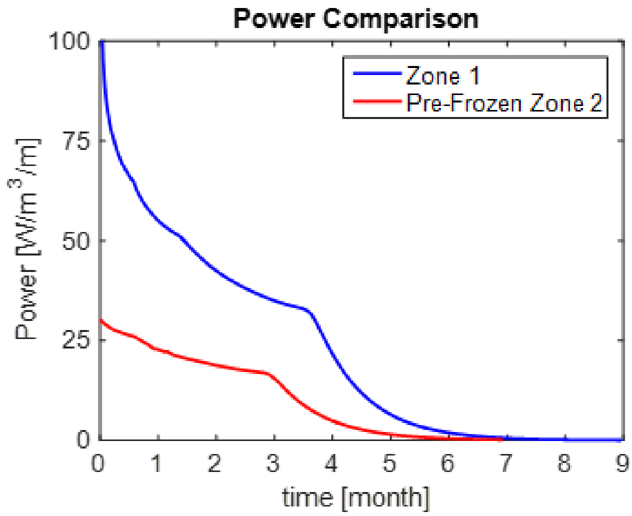


Figure 9. 3D simulation: Comparison of cold energy stored in Zone 1 vs. cold energy extracted by Zone 2 over time

## V Conclusions

The idea of energy saving due to pre-freezing the upcoming mining zone, by using/extracting cold energy from the back-filled zones, is validated in this study as technically feasible. Numerical and experimental results suggest that the excess cold energy can be transferred from the back-filled zones to the new mining zones; resulting in energy savings and shorter freezing time. In summary the following are the conclusions from this study:

1. Mining a scattered ore in sequence, involving ground freezing prior to mining a zone, has the potential to be optimized in terms of energy consumption and freezing time.
2. Pre-freezing a zone using the excess cold energy stored in the mined zone is a technically feasible idea that can shorten the freezing time from 9 to 7 months and can save up 37% of energy.
3. The technical feasibility of the idea is confirmed by the data from experimental study and mathematical model; validated to represent physically tennable solution.
4. Further energy savings can be achieved if freeze pipe design is improved.

Economic feasibility of the idea is unclear and further research studies or mine-specific economic feasibility studies are required to validate the idea before implementation. This can be a potential future research work. It is thus recommended to use this study as a technical baseline to make informed decisions at a mine to support energy saving initiatives at uranium mines such as McArthur River Mine and Cigar Lake Mine.

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