THERMAL ANALYSIS OF AN EXPERIMENTAL THERMOSYPHON INSTALLED AT THE GIANT MINE IN YELLOWKNIFE, NT, CANADA

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ABSTRACT
The Giant Mine is a gold mine located in Yellowknife, NWT, which began operating in 1948. The gold extraction process generated highly toxic residues in the form of an arsenic trioxide dust (As_2O_3). About 237,000 tonnes of dust are currently stored underground in mined out stopes or purpose-built chambers to depths reaching 100 m. The selected remedial method consists of encapsulating the arsenic dust by freezing the surrounding ground. An experimental thermosyphon was constructed to confirm the capability of thermosyphons to depths reaching 100 m. This paper describes the construction of the experimental thermosyphon, the instrumentation, the collected data and the thermal analysis. The data indicate that thermosyphon is capable of developing freezing conditions along its 100 m length and that it is performing according to the initial design. The thermal properties of the surrounding ground were calculated by calibrating a thermal model.

RÉSUMÉ
La mine Giant est une mine d'or située à Yellowknife, TNO, qui débuta ses opérations en 1948. Le procédé d'extraction de l'or entraîna la production de résidus hautement toxiques composés de poudre de trioxyde d'arsenic (As_2O_3). Environ 237,000 tonnes de cette poudre est présentement entreposées sous terre à l'intérieur de tailles exploitées ou de chambres construites spécifiquement pour la poudres, et ce, à des profondeurs atteignant 100 m. La méthode corrective choisie consiste à encapsuler la poudre en gelant le sol environnant. Un thermosyphon expérimental fut construit afin de confirmer leur fonctionnement à une profondeur de 100 m. Cet article décrit la construction du thermosyphon expérimental, l'instrumentation, les données recueillies ainsi que les analyses thermiques. Les données indiquent que le thermosyphon peut refroidir le sol sur une longueur de 100 m et rencontre les critères de design. Les propriétés thermiques du substratum rocheux sont calculées en calibrant un modèle thermique.

1. INTRODUCTION

The Giant Mine, located in Yellowknife, NWT, has been producing gold since 1948, which led to the production of residues in the form of an arsenic trioxide dust (As_2O_3). About 237,000 tonnes of dust are currently stored underground in mined out stopes or purpose-built chambers to depths of about 100 m. The dust contains about 60% arsenic, which is hazardous to both humans and the environment. The work presented herein is part of the Giant Mine Arsenic Trioxide Project which was initiated to identify methods that could provide a long-term management alternative for the arsenic trioxide dust currently stored underground (SRK 2002). Encapsulating the arsenic dust by freezing the ground around the chambers and stopes has been selected as the preferred remedial method. Active freezing such as conventional brine system or hybrid thermosyphons will likely be used to initially freeze the ground. An alternative under consideration to maintain the frozen condition is passive freezing using thermosyphons but the required depth of 100 m has never been attempted before. There was concern that an adiabatic cycle could develop within the thermosyphon over this depth, preventing it from functioning effectively. An experimental thermosyphon was therefore constructed to confirm the capability of thermosyphon to operate at depths reaching 100 m, to determine the heat extraction rate achieved by the thermosyphon, and to characterize the thermal properties of the surrounding ground. The experimental thermosyphon was instrumented and an adjacent hole, drilled about 2.1 m away, was also instrumented to monitor the adjacent ground temperature.

This paper describes the construction of the experimental thermosyphon, the installation of the instrumentation, the data collected to date and the calculation of the thermal properties of the bedrock from thermal modelling.

2. BACKGROUND INFORMATION

2.1 Climate Data

Weather data for Yellowknife was obtained from the weather station at the airport. The coordinates for that station are 62°28' N, 114°27' W, and the elevation is 205 m. The average ambient temperature is -5.2 °C based on measurements from 1942 to 1990 inclusive. Aspler (1978) reported a freezing index of 3400 °C days and a thawing index of 1700 °C days for Yellowknife.

2.2 Surface conditions and geology

The topography at Giant Mine is undulating, with extensive areas of exposed bedrock on the higher ground, and minor deposits of glacial till in low lying areas. The overburden consists primarily of clay and silt with some sand and gravel. The bedrock around the arsenic chambers and stopes consist of sericite schist and chlorite schist.

2.3 Thermosyphons

Thermosyphons are long hollow tubes containing pressurized carbon dioxide (CO_2) gas and CO_2 liquid as illustrated in Figure 1. The tubes are installed in drilled holes, with a short length left to extend above the ground surface. A radiator is attached to the above-ground portion, which consists essentially of a 25 mm coil welded in spiral around the pipe (see Figure 2). Any heat in the ground causes the CO_2 liquid within the tube to evaporate and rise upwards to the radiator. If the radiator is cold, as it would be throughout a Yellowknife winter, the CO_2 gas condenses and the liquid runs back down the tube, where it can be evaporated again. The cycle of CO_2 evaporation in the tube at depth and condensation at the surface acts as a heat pump, effectively drawing heat out of the ground.

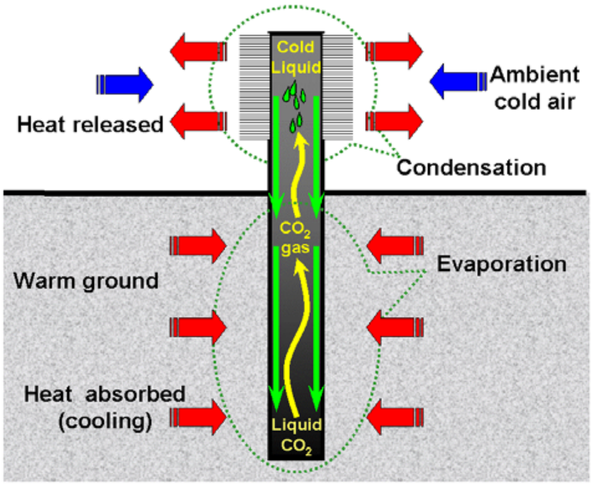

Figure 1. Schematic description of a thermosyphon during winter

Thermosyphons have been in widespread use for over 25 years. However, most applications of thermosyphons are shallow, for example for preventing the thawing of permafrost below roads or buildings (Haynes and Zarling 1988, Yamak and Long 2002). In order to freeze the ground around the arsenic chambers and stopes, thermosyphons would need to be effective at depths up to 100 m.

3. FIELD DATA

3.1 Drilling

The construction of the experimental thermosyphon consisted of drilling two vertical holes. One hole was used for the thermosyphon and the second was drilled about 2.1 m away to monitor the temperature in the adjacent bedrock. The drilling was carried out in December 2001.

Figure 2. Close-up photo of the radiator of the thermosyphon installed at the Giant Mine.

The two holes were drilled through overburden and encountered bedrock at a depth of about 6.1 m. The drilled holes were terminated at depths of 100 m (thermosyphon) and 99.4 m (instrumented drillhole). The encountered bedrock consists primarily of sericite schist. A possible fault zone was encountered in the bottom 3.9 m of the holes. Permafrost was encountered within the overburden layer.

3.2 Hole alignment measurements

The hole for the thermosyphon and the instrumented drillhole were both surveyed for vertical alignment before the construction and installation of the thermosyphon. The purpose of this survey was to measure the distance between the thermosyphon and the adjacent instrumented drillhole.

Six measurements were taken at various depths inside both holes and the results are shown in Figure 3. The horizontal distance between the two holes is 2.1 m at the surface and gradually increases to 2.8 m at a depth of 88.4 m.

3.3 Construction of thermosyphon

The experimental thermosyphon was constructed by Arctic Foundation of Canada Inc. between February 25 and March 2, 2002. The 100 m portion of the thermosyphon below the ground surface was constructed using steel pipe sections having an outside diameter of 73 mm and a wall thickness of 5.16 mm (ASTM A53 - 73.0 O.D. x 5.16 STD/Sch. 40). The above-ground section of the thermosyphon was constructed with 88.9 mm diameter pipe at a height of 8.4 m above grade, with the radiator being 6.3 m long. Figure 4 provides some details on the thermosyphon. Further details are provided in SRK (2002).

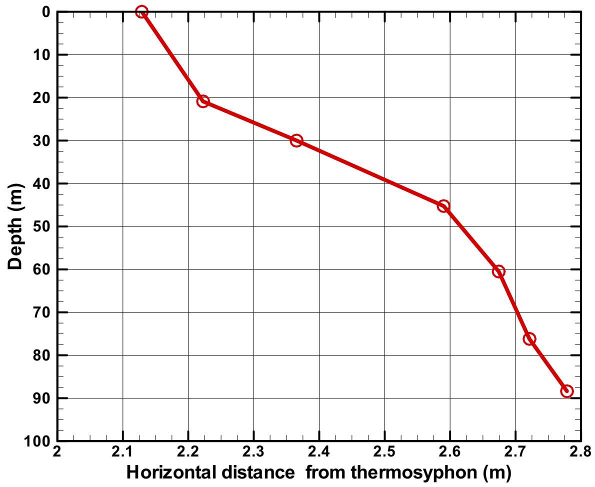

Figure 3. Horizontal distance between the thermosyphon and the adjacent instrumented drillhole.

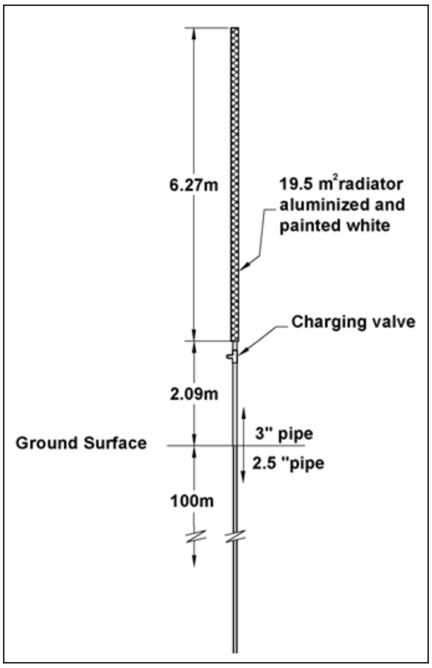

Figure 4. Details of the thermosyphon installed at the Giant Mine

The upper 6.3 m section is covered by a 1 inch wide steel coil that acts as the radiator. This arrangement provided a surface area of about 19.5 m^2 for heat exchange. The exposed steel above the ground surface and down to about 1 m below grade was aluminized and painted white to increase heat losses. After the thermosyphon was installed in the drillhole, the annular cavity around the pipe was backfilled with commercial grade silica sand. The thermosyphon was then charged with CO_2 through the charging valve at the bottom of the radiator section.

3.4 Instrumentation

Instrumentation was installed to monitor ambient air temperature, wind speed, temperature at various depths and on the radiator of the thermosyphon, and temperature in the adjacent instrumented drillhole. The data are collected using a datalogger that is programmed to store measurements on a daily basis. The automated monitoring system was installed during the construction of the thermosyphon and has been in operation since March 2002.

The temperatures are measured using RTD (Resistance Temperature Detector) sensors. The RTD sensors installed on the thermosyphon were embedded in silicon and then attached to the pipe of the thermosyphon. The RTD sensors installed in the instrumented drillhole were simply lowered into the hole, which was then backfilled with commercial grade silica sand. Twelve RTD sensors were installed on the thermosyphon (9 below ground surface and 3 on the radiator) and eleven sensors in the adjacent drillhole. The instrumented locations are as follows:

- Thermosyphon – below ground surface: 10, 20, 40, 50, 60, 70, 80, 90 and 100 m;
- Thermosyphon – above ground surface (radiator): 0.5, 3 and 6.25 m; and
- Instrumented drillhole: 5, 15, 25, 35, 45, 55, 65, 75, 85, 95 and 100 m.

Wind speed and ambient temperature are measured at the top of the thermosyphon, above the radiator section.

3.5 Temperature Measurements

The initial ground temperature in the vicinity of the thermosyphon is shown in Figure 5. It shows that the ground temperature was between -0.5 and +2.5 °C; the geothermal gradient was originally about 29.6 °C/km; and the permafrost was present down to about 23 m below the surface. The geothermal gradient is the inverse of the slope of the linear portion of the ground temperature profile.

The behaviour of the thermosyphon is demonstrated in Figure 6, where the temperature along the thermosyphon is compared to the ambient air temperature. The grey curves represent the three temperature sensors on the radiator; the black curves represent the temperature on the thermosyphon at various depths; and the circles, the daily average ambient air temperature. This figure shows that the thermosyphon begins extracting heat (cooling) once the ambient air temperature is colder than the ground surrounding the thermosyphon. This "trigger" temperature is essentially the average ground temperature along the thermosyphon. In the case of the Giant Mine, it occurs in the vicinity of 0 to +2 °C as shown in Figure 5. Figure 6 shows that the thermosyphon reached -15 °C during the coldest part of the winter. The cooling process terminates when the ambient air temperature becomes warmer than the ground temperature and the thermosyphon reverts back to the surrounding ground temperature. The warm segments for which the thermosyphon is “dormant” are shown by the plateaus that remain near 0 °C while the ambient air temperature is warmer.

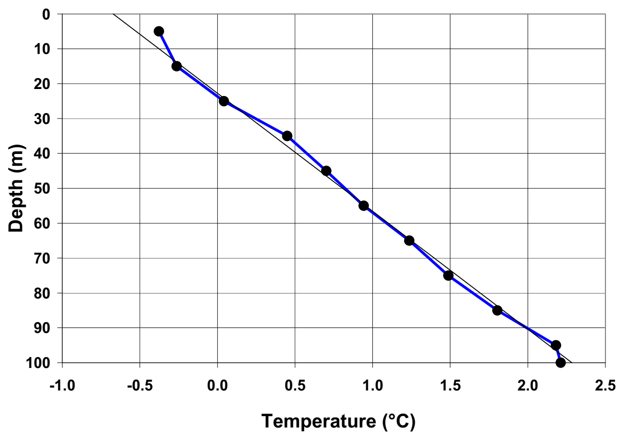

Figure 5. Initial ground temperature profile inside the instrumented drillhole.

Figure 6 also shows that the temperature of the radiator remains warmer than the ambient air temperature during the winter months, indicative of heat being released through the radiator.

The black lines in Figure 6 show of all the temperatures measured along the thermosyphon. Even though the nine measurement points are distributed over 100 m, the temperatures are almost identical. These data suggest that the thermosyphon functions effectively over its entire 100 m depth.

The small temperature variation along the thermosyphon is illustrated in Figure 7, where the contours represent the difference along the thermosyphon relative to the top RTD sensor. With the exception of the bottom RTD sensor at 100 m, the temperature difference is essentially less than 1 °C between the top RTD sensor at 10 m below the ground surface and the one situated at 90 m depth. The bottom RTD sensor exhibits much colder temperatures, which are attributed to a faulty RTD sensor.

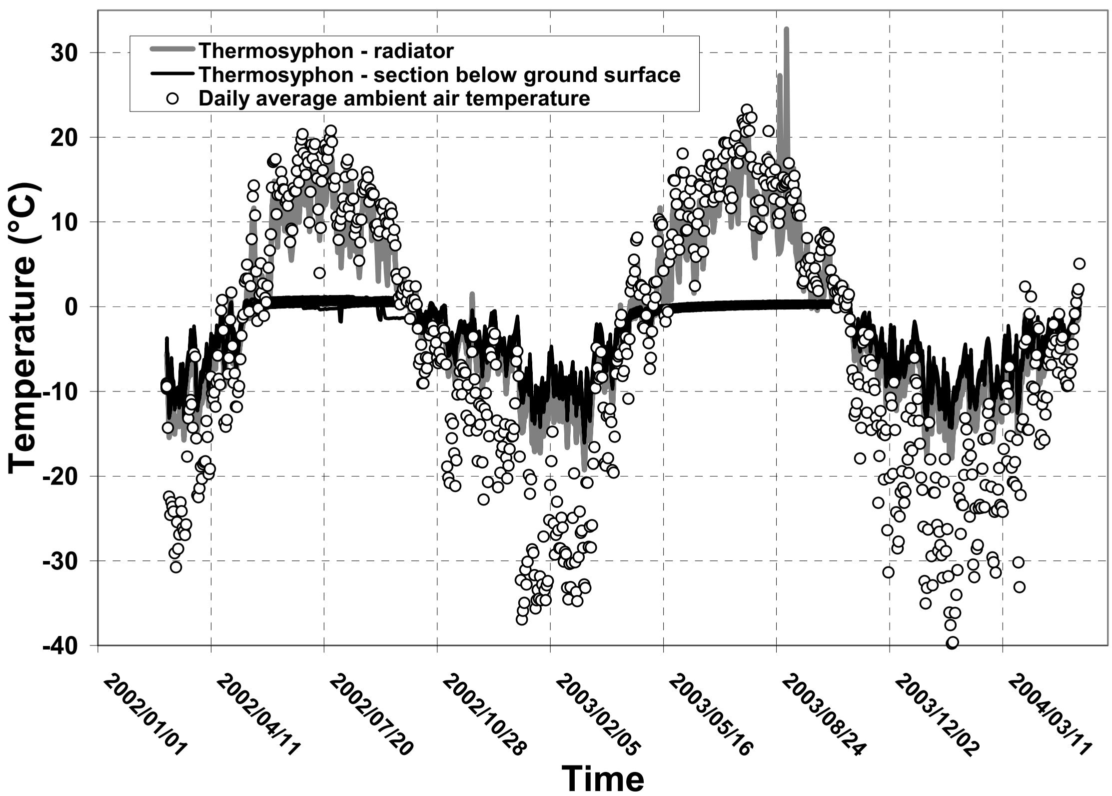

Figure 6. Temperature comparison of the thermosyphon, the radiator and the ambient air.

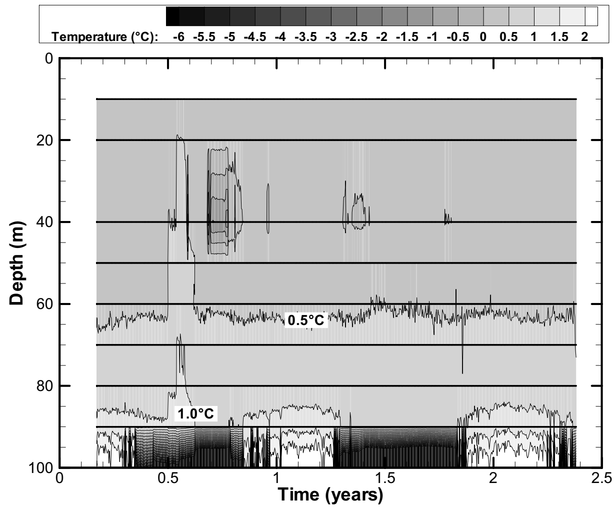

Figure 7. Temperature variation along the thermosyphon, difference relative to the top RTD sensor located at 10 m.

Figure 8 shows the temperature variation inside the instrumented drillhole. The downward slope of the isotherm (temperature decrease) corresponds to the periods when the thermosyphon is extracting heat while the upward slope (temperature increase) occurs when the thermosyphon is "dormant". The heat increase is caused by the surrounding bedrock mass going to thermal equilibrium once the thermosyphon has ceased to extract heat. It is possible to see from Figure 8 that the ground temperature around the thermosyphon is decreasing from one annual cycle to the next, but at a slower rate than is observed within each year.

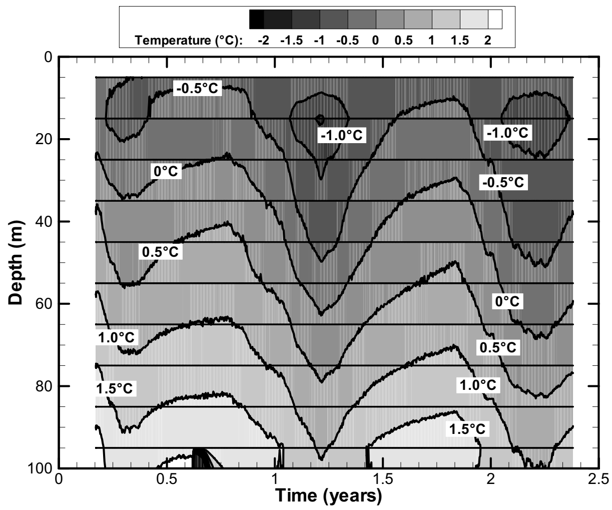

Figure 8. Ground temperature inside the adjacent instrumented drillhole.

The temperature variation in the instrumented drillhole is better illustrated in Figure 9 where the contours represent the temperature difference relative to the measurements taken shortly after the installation (March 2002). It shows that the ground temperature decreased by up to 1 °C at the end of both winters, and that the temperature decrease lasted longer during the second winter. It also shows that the temperature increased back to the initial levels when the thermosyphon was "dormant" in the summer, although this "warm" period decreased after the second winter. This confirms that the ground is slowly getting colder.

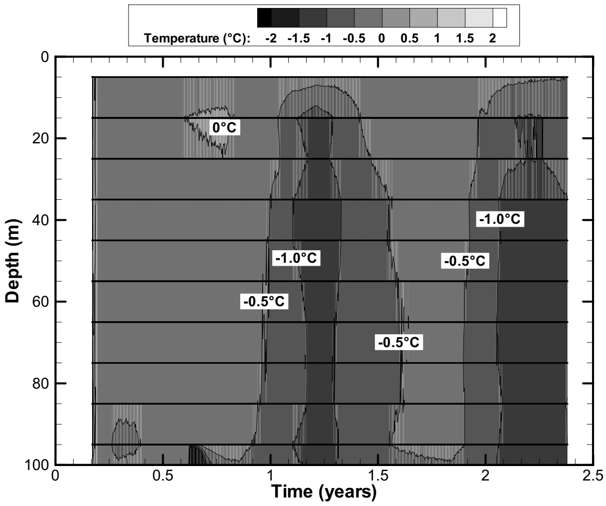

Figure 9. Temperature difference relative to the measurements taken in March 2002.

4. THERMAL MODELLING

4.1 Scenario

The thermal modelling consisted of reproducing the heat exchange between the thermosyphon and the surrounding bedrock, and using the temperature measured inside the adjacent instrumented drillhole to calibrate the thermal properties of the bedrock. The calibration was achieved by adjusting the thermal conductivity and the heat capacity values of the bedrock and by using the temperature measured along the thermosyphon as a boundary condition.

4.2 Setup

The model geometry reproduced a 1.0 m thick slice centered at the depth of a RTD sensor inside the adjacent instrumented drillhole. The geometry was represented in 3D using an axisymmetric domain with the thermosyphon near the origin. As illustrated in Figure 10, the boundary near the axis of symmetry corresponds to the outer face of the thermosyphon at a radius of 0.0365 m (outside diameter of 73 mm). The sand backfill around the thermosyphon was also included in the model and has a thickness of 0.0245 m. The remainder of the domain represents the bedrock formation, which was considered isotropic over the entire domain. The outer boundary was set at a radius of 30 m to minimise the effects of the outer boundary conditions.

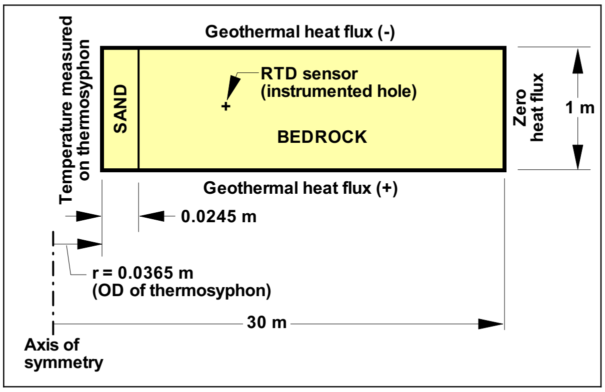

Figure 10. Dimensions and boundary conditions used in the thermal model.

The thermal model was applied to two 1.0 m segments: 55 and 65 m depths. These two depths correspond to locations where RTD sensors were installed inside the adjacent instrumented drillhole.

The model output temperature was extracted according to the offset distances shown in Figure 3. The simulations for the segment at the 55 m depth consisted of extracting the ground temperature at a radius of 2.64 m, while the 65 m depth, the extracted data was at a radius of 2.69 m.

The time dependent simulations covered the period between March 4, 2002 and May 18, 2004, for a total of 803 days.

The initial condition consisted of specifying a constant temperature over the entire domain based on the ground temperature measured on March 4, 2002 (time zero). The ground temperature was 0.941 °C at 55 m and 1.234 °C at 65 m.

The boundary conditions are indicated in Figure 10 and were as follows:

• Bottom and top boundaries: heat flux based on the geothermal gradient measured at the thermosyphon and the thermal conductivity of the bedrock. Both boundaries had the same heat flux value, with the bottom one being positive (heat inflow) and the top being negative (heat outflow).

The value of the heat flux was calculated from the measured geothermal gradient at the thermosyphon and the estimated thermal conductivity using the following expression:

$$q = ki \quad [1]$$

where q = geothermal heat flux (J m^{-2} day^{-1})
k = thermal conductivity (J m^{-1} day^{-1} °C^{-1})
i = geothermal gradient = 29.6 °C km^{-1}

• Inner boundary (outer face of the thermosyphon): temperature dependent using the daily average temperatures measured on the thermosyphon. The temperature on the thermosyphon measured at 50 and 60 m was averaged and used for the boundary condition in the simulations that targeted the RTD sensor 55 m. The temperature measurements on the thermosyphon at 60 and 70 m were used for the simulations at the 65 m depth. Figure 11 shows the temperature data that was used in the simulations for both the 55 and 65 m depths. There is very little temperature difference between the 50 to 60 m and the 60 to 70 m zones.

• Outer boundary: zero heat flux

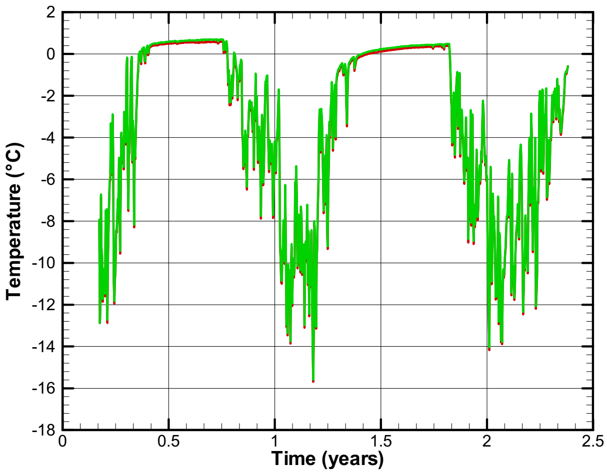

Figure 11. Average daily temperature on the thermosyphon used as boundary conditions for the thermal model.

4.3 Ground properties

The model has two zones: the sand backfill and the bedrock. Both materials were considered unsaturated since the thermosyphon is located within the dewatered area of the Giant Mine.

The thermal properties of the sand backfill were estimated using the method developed by Johansen (1975). The estimated property values are:

- Porosity: 0.30
- Degree of saturation: 20%
- Quartz content: 20%
- Bulk dry density: 1869 kg m-3

- Thermal conductivity
  - unfrozen: 106 kJ m^{-1} day^{-1} °C^{-1}
  - frozen: 78 kJ m^{-1} day^{-1} °C^{-1}
- Volumetric heat capacity:
  - unfrozen: 1582 kJ m^{-3} °C^{-1}
  - frozen: 1456 kJ m^{-3} °C^{-1}

Based on the recovered rock cores, the porosity of the bedrock was estimated at 1% and the degree of saturation was estimated at 50%. The thermal conductivity and the volumetric heat capacity were both determined from the calibration of the thermal model.

4.4 Results and Discussions

The calibration of the thermal model was achieved by using a thermal conductivity value of 300 kJ m^{-1} day^{-1} °C^{-1} and a volumetric heat capacity of 2386 kJ m^{-3} °C^{-1}. The thermal conductivity was the most sensitive parameter, and, therefore, was used as the main parameter for the calibration. The model was relatively insensitive to the heat capacity.

Figures 12 and 13 show the results from the calibrated model for the RTD sensor located at 55 and 65 m. Both figures show that the thermal model was able to reproduce the thermal regime around the thermosyphon. The calibrated model is well within the accuracy of the instrumentation, and provides a strong basis for predicting the rate of ground freezing that could be attained from banks of thermosyphons installed around the Giant Mine arsenic trioxide stopes and chambers.

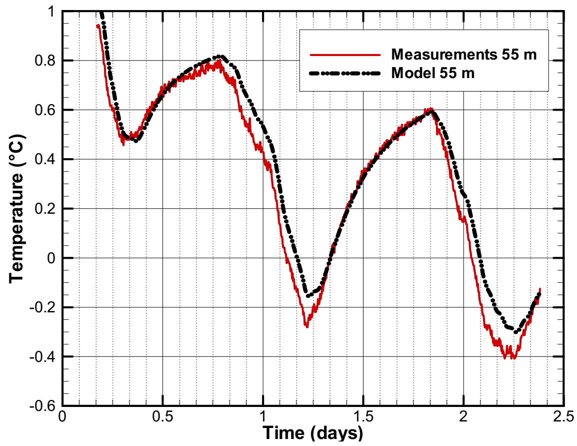

Figure 12. Calibrated thermal model, measured and predicted ground temperatures at 2.64 m from the thermosyphon and 55 m deep.

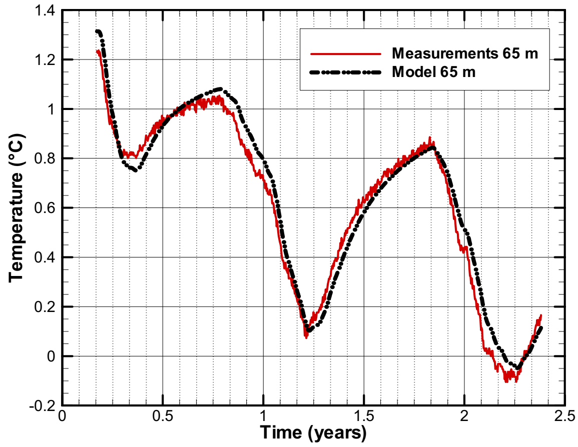

Figure 13. Calibrated thermal model, measured and predicted ground temperatures at 2.69 m from the thermosyphon and 65 m deep.

5. CONCLUSIONS

The data collected to date indicates that thermosyphon is capable of developing freezing conditions along its 100 m length and that it is performing as expected. This is confirmed by the temperature measurements inside the adjacent instrumented drillhole.

The thermal model was able to reproduce the thermal regime measured around the thermosyphon and enabled the estimation of the thermal properties of the surrounding bedrock.

6. ACKNOWLEDGEMENTS

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